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What Is a Feasible and 1.5°C-Aligned Hydrogen Infrastructure for Germany? A Multi-Criteria Economic Study Based on Socio-Technical Energy Scenarios

Abstract

Emission-free hydrogen (H2) is crucial to decarbonize energy supply and to tackle the climate crisis. To unlock the potential of H2, pipelines infrastructures and related investments are required to enable trade. However, it is uncertain what future H2 infrastructure will be needed. The paper aims to assess three H2 infrastructures for Germany within a European context in terms of feasibility (criterion 1) and 1.5°C-alignment (criterion 2) to inform investment and political decisions. Own socio-technical scenarios are used to include findings from four disciplines for a holistic infrastructure evaluation. As results, implementation requirements are identified that determine the future robustness of different supply chains. It is assessed which feasible infrastructures are 1.5°C-aligned in terms of impact for the environment and energy transition, which goes beyond the German context. The results show, that the origin of H2 mainly determines the 1.5°C-alignment and that renewable H2 is more sustainable than fossil-based H2. Also, investments in gas pipelines for future retrofitting might delay energy transitions due to lock-ins and climate-related risks. In conclusion, a step-by-step construction of new H2 pipelines for renewable H2 near industry cluster is advisable. In the light of the chick-and-egg problem of establishing a H2-economy, recommendations on H2 supply and demand are drawn, which are also relevant for an international context.

JEL-Code: H54, Q42, Q48, O33

Keywords: Energy transition; socio-technical scenarios; H2 infrastructure; energy policy; climate risks

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1.1 Introduction

Hydrogen (H2) is needed according to numerous energy scenarios (IEA 2021; IRENA 2020; World Energy Council 2019) for decarbonized energy supply. H2 can be used as a low-carbon energy carrier, energy storage, fuel and feedstock across different sectors and industries (IEA 2019a). Governments of countries, such as Korea (MOTIE 2019), Australia (Australian Government 2019) or France (French Government 2018), but also the European Union (EU Commission 2020), have published H2 strategies to promote the development of H2 economies. As a frontrunner of energy transitions, Germany published its H2 strategy in 2020 (BMWi 2020) followed by roadmaps on the level of states (e.g. MWIDE2 2020).

To unlock the potential of H2 and boost H2 economies, pipeline infrastructures for H2 are needed to enable transport and trade. For a H2 infrastructure, large private investments and political decisions are required today. Economic private actors primarily construct and operate Germany's energy infrastructure and the government sets the underlying conditions. However, these decisions are characterised by uncertainties and are not trivial for multiple reasons. It is uncertain how the H2 infrastructure will look like and what requirements must be met (Wietschel et al. 2006).

First, supply chains can develop in different ways. The development depends on the main type of H2 that will be used, where it gets produced and where and in which sectors it will be used for what use cases. These developments are influenced by how the energy transition unfolds. Second, building a H2 infrastructure is part of establishing a H2 economy and relates to the three-fold chicken and egg problem of coordinating what comes first – supply, demand or infrastructure. Third, for the development of a H2 infrastructure, the future of the gas grid and fossil natural gas is important (Hickey et al. 2019). The question is whether new pipelines for H2 should be built (van de Graaf et al. 2020) or existing gas pipelines should be repurposed for H2 or admixture into the natural gas grid. Fourth, although only green H2 which is produced from renewable energy is sustainable in the long run (SRU 2021a), the use of non-renewable H2 is also discussed (Howarth and Jacobson 2021; Noussan et al. 2021) and important for the design of H2 infrastructures. Finally, it needs to be considered that energy infrastructure shapes the energy system and associated emissions for decades. Due to its long technical lifespan, infrastructures may need to retire prematurely to meet the Paris Agreement (Tong et al. 2019).

Consequently, inadequate infrastructure decisions can cause economic ricks, such as the climate-related risk of asset stranding, negative environmental and a delay of energy transitions due to fossil lock-ins (Kemfert et al. 2022). Considering the urgency of climate mitigation, these risks are problematic from a (political) macro-perspective and for economic actors. These issues show that not only techno-economic aspects are relevant for H2 infrastructures and that climate-goal compatibility has become an important factor for economic success and should thus be considered in investment and political decisions.

The author proposes that the evaluation and investment decisions for H2 infrastructure should be based on two criteria, namely 1) *feasibility* and 2) *1.5°C-alignment*. The aim of this paper is to evaluate three H2 pipeline infrastructure options within a European H2/CCS chain in terms of their 1) *feasibility* and 2) *1.5°C-alignment* to inform investment and political decisions. The following research question is answered: *What is a feasible and 1.5°C-aligned H2 pipeline infrastructure for Germany?*

The criterion of *feasibility* is based on the understanding that energy systems are socio-technical systems (Grubler 2012; Markard et al. 2012). How these systems develop depends on economic, political, social and technical aspects (Miller et al. 2015; Cherp et al. 2018). Energy transitions are therefore seen as socio-technical transitions (Pregger et al. 2020; Geels et al. 2017). Based on Hoffart et al. (2021), Schubert et al. (2015), Majone (1975), the author defines feasibility as a high chance for successful implementation. A H2 infrastructure is feasible from a forward-looking perspective if it is not only technically but also legally, economically and sociologically feasible and finds majorities in decision-making. Doing so follows Majone (1975) who argues that all constraints need to be fulfilled for feasibility, which is why implementation requirements are identified in this paper.

The criterion of *1.5°C-alignment* requires climate-goal compatibility to be considered as an economic factor for H2 infrastructure investment and policy decisions. It implies a backward-looking perspective from an emission-free future to the present and investigates the impact of H2 infrastructures on the environment and energy transitions, considering the remaining emission budget.

The author combines a qualitative scenario analysis (QSA) with a weighted sum analysis in a wider sense, which represents a simple, non-formal version of a multi-criteria decision analysis (MCDA). Six qualitative socio-technical scenarios are used as an evaluation framework for the forward-looking implementation analysis. Findings from law, engineering, economics and sociology are included to assess *implementation requirements* (criterion 1.1) and the *future ro-*

bustness (criterion 1.2) of three infrastructure options. For the backward-looking ambition analysis, the H2 infrastructure's *impact on the environment* (criterion 2.1) and *on energy transitions* (criterion 2.2) is investigated (see Figure 1).

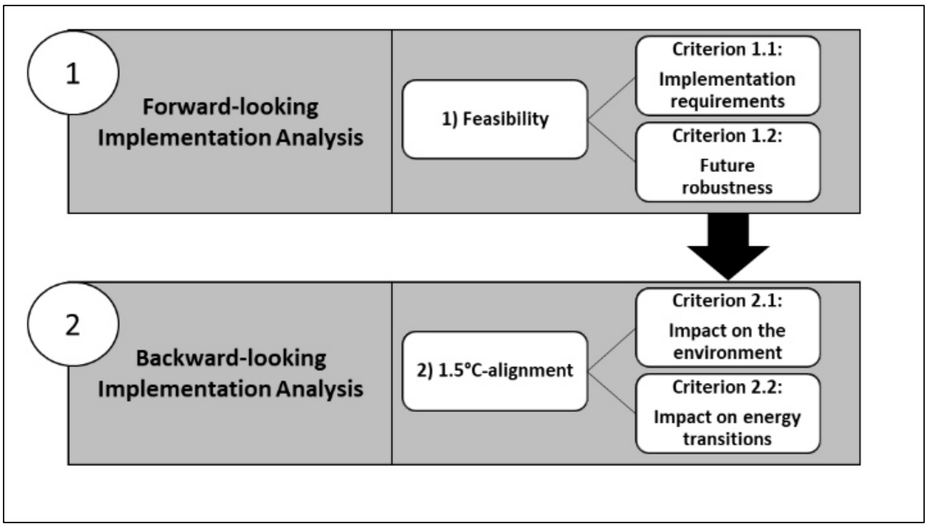

Figure 1: Approach and evaluation criteria.
Source: Author's elaboration.

No economic study has yet analysed the feasibility and 1.5°C-alignment of H2 infrastructures in Germany using socio-technical scenarios. The paper is the first one that combines qualitative scenario analysis with the assessment of different criteria to include findings from different disciplines (economics, sociology, law and engineering) for an economic energy infrastructure assessment.

Such a study is valuable, as Cherp et al. (2018) point to a lack of approaches on how to integrate various discipline's findings (Cherp et al. 2018). While Geels (2002) describe transitions as social-political feasibility problem, Majone (1975) sees a need to consider feasibility (constraints) in decision-making and economic analysis (Majone 1975). In the literature, socio-technical scenarios and energy scenarios are considered a valuable tool to study the feasibility of energy transitions (Geels et al. 2020) and transition policies (Elzen et al. 2002; Rogge et al. 2020), investment and political decision in energy transition, (Schubert et al. 2015), including hydrogen futures (McDowall and Eames 2006). Hahn et al. (2020) provide an overview of energy scenarios for Germany, Weimer-Jehle et al. (2020) review socio-technical energy scenarios. Several socio-technical scenarios investigate the German energy transition (Vögele et al. 2017; Vögele et al. 2019; Pregger et al. 2020; Witt and Klumpp 2021). While there are socio-technical H2 scenarios for the UK (McDowall 2014), there are, to the author's knowledge, non for Germany, including H2 infrastructure. Research on H2 infrastructure for Germany is mainly technical (Reuß et al. 2019; Husarek et al. 2021) and investigates the interaction with other sectors (Gils et al. 2021), pipeline planning (Baufumé et al. 2013), gas pipeline retrofitting (Cerniauskas et al. 2020; Yoon et al. 2022), but also important stakeholders (Schlund et al. 2022). H2 infrastructures are evaluated using different criteria, such as (demand) uncertainty (Dayhim et al. 2014; Kim et al. 2008; Nunes et al. 2015), costs and safety (Kim, J., Moon, I. 2008), risk and sustainability (Markert et al. 2017) or emission reduction (Wietschel et al. 2006; Balcombe et al. 2018). To the author's knowledge, the 1.5°C-goal was studied in the context of energy infrastructure in general (Artelys 2020; Tong et al. 2019), but not with regard to H2 infrastructure in specific. Political and social feasibility is addressed related to climate mitigation (Jewell and Cherp 2020), adaptation options (Singh et al. 2020) and in energy scenarios (Schubert et al. 2015), economic analysis (Majone 1975), feasible implementation scenarios (Trutnevyte et al. 2012) or low-carbon transitions (Geels et al. 2020). Feasibility in a wider sense, such as proposed by Hoffart et al. 2021), was not yet applied as a criterion yet.

The paper contributes to the economic literature on energy transition and effective transition policies, as well as energy transition research in multiple ways: New insights on accelerating the establishment of a H2 economy through infrastructure building in Germany are providing, which offer guidance also for other countries. A new approach is proposed of how to use scenario analysis and findings from different disciplines a holistic energy infrastructures assessment. The paper provides criteria for effective transition decision-making and a holistic infrastructure evaluation in the light of the climate crisis.

The remainder is structured as follows. In section 3.2, the infrastructure options, the socio-technical scenarios, and the approach are described. Section 3.3 displays the results of the implementation and ambition analysis. First, feasible H2 infrastructures are identified based on six socio-technical scenarios. Second, the 1.5°C-alignment is analysed referring to environmental and economic consequences. Section 3.4 discusses limitations and key insights. The paper ends with recommendations and concluding remarks.

1.2 METHOD

In this section, the three infrastructure options and six socio-technical scenarios (see section 3.2.1), as well as the paper's approach (see section 3.2.2) are described in depth.

1.2.1 The infrastructure options and scenarios

In the German context, three infrastructure options for deep decarbonisation are examined (see Table 1). They differ concerning the role of the natural gas grid and the type of H2 and thus comprise different requirements. Option 1 represents a special case. Deep decarbonisation occurs decentral via carbon capture and transport (CCT) without changing the energy carrier which requires pipelines for CO2 not for H2. Due to Germany's geopolitical role as a gas transition country, the different options are embedded within a European H2-CCS chain. The success of energy transitions, thus, also depends on cooperation's with third-party countries. For reasons of simplicity, one export country of blue H2 (Norway) and one supplier of offshore carbon storage (Netherlands) are considered.

Table 1: The case study.

	Options	***Description***	***Infrastructure adaption***	***Role of H2***
1)	CO2 pipelines to export CO2 for off-shore CCS	Decarbonisation of large emitters via CCT for off-shore storage abroad.	• No changes in the existing NG grid • New CO2 infrastructure	• H2 usage as today • Mainly grey H2
2)	Retrofitting gas pipelines for H2 admixture	Blue H2 from Norway is blended in the German natural gas grid	• Changes to the natural gas grid for higher H2 Shares • No need for new pipelines	• Focus on blue H2 • Minor role of green H2
3)	New H2 pipelines for pure H2	New pipelines for pure H2, imported from Norway and domestically produced.	• No changes to the existing natural gas grid • New H2 pipelines	• Focus on pure H2 • Role of green vs. blue H2 uncertain

Source: Author's elaboration.

The infrastructure options are assessed using six socio-technical qualitative energy scenarios (see Table 2), which were developed by the author based on methodological considerations of Hoffart et al. (2021). The scenarios show different consistent future developments of conditions that are relevant for a H2 infrastructure in 2035 and consider the German energy transition and sector coupling. As the focus is neither on the scenarios itself nor on their development, detailed information on key factors and relevant stakeholders can be found in the appendix (see Table A.1, Table A.2).

Table 2: Socio-technical qualitative scenarios.

Scenarios	***Short description***
Fossil revival instead of green progress	Due to a low political ambition, there are no plans for a natural gas exit and no support for H2 technologies or electrification. There is a strong fossil lobby. Mobility and heating are still dominated by fossil-based solutions. While demand for natural gas increases, there is low demand for renewable H2 which is satisfied by H2 imports.
Technology-open green transformation	Due to high political ambition and lots of available resources, there are plans for a natural gas exit and renewable gas quota, as well as extensive support for both H2 and electrification. Both e- and H2 technologies strongly increase in the heating and mobility sector. The high demand for renewable gas is satisfied through an increased German H2 production and high imports. There is strong lobbying for the transformation.
Green transformation with H2	Due to high political ambition and lots of available resources, there are plans for a natural gas exit and renewable gas quota, as well as extensive support for both H2 and electrification. There is strong increase in H2 technologies for mobility and heating. The high demand for renewable gas is satisfied by both an increased German H2 production and high imports. There is strong lobbying for the transformation.
Incremental green transformation	Despite a high amount of available resources, there is low support for H2 and electrification, but plans for a natural gas exit. There is a moderate increase of e- and H2 technology in the heating and mobility sectors. The small demand for renewable gases is satisfied by imports. The lobby supporting the transformation is weak.
Top-down effort and conflicting interests	Due to high political ambition and lots of available resources, there is extensive support for both H2 and electrification, as well as plans for a natural gas exit. Mobility and heating are dominated by fossil-based solutions. The small demand for renewable gas is satisfied by imports. The fossil lobby is strong and dominating.
Bottom-up effort & political inaction	As the political ambition and available resources are low, there are no plans for natural gas exit or renewable gas quota, as well as no support for H2 technologies and electrification. There is a moderate increase of e- and H2 technology in the heating and mobility sectors. While the demand for renewable gas is high and German H2 production increase, imports are rather low. The lobby supporting the transformation is strong.

Source: Author's elaboration.

Qualitative scenarios describe how the future might develop, which is based on consistent assumptions (Guivarch et al. 2017). QSA does not aim to identify *the* most likely future, but a *variety of possible, consistent* future developments, without assigning probabilities (Kosow and Gaßner 2008), but including extreme events (Gausemeier et al. 1998) and participatory elements (Wright et al. 2013; Ernst et al. 2018). Energy scenarios are widely used to assess decarbonisation (Weimer-Jehle et al. 2020) including infrastructure aspects. In this paper qualitative energy scenarios are used for two reasons: First, as energy systems are not only technical but rather socio-technical systems (Geels et al. 2020), it is crucial to consider the socio-political context (Weimer-Jehle et al. 2020), social acceptance (Glanz et al. 2021), political feasibility (Schubert et al. 2015), stakeholder's interest (Mielke et al. 2016), as well as complexity and uncertainty (Hoffart et al. 2021) for investment and political decisions. It is an interdisciplinary task (Hoffart et al. 2020) and requires to consider findings of different discipline (Cherp et al. 2018). In contrast to quantitative scenarios, which are often criticised of being too narrow due to a strong techno-economic focus (Miller et al. 2015; Ansari and Holz 2019), qualitative scenarios consider these aspects (Hoffart et al. 2021). Second, there is the risk that investments and political decision fail when they are designed for a specific future which does not materialize or does not find majorities. QSA can help to identify future-robust investment and policy decisions which fit to changing conditions, as key factors are considered (Hoffart et al. 2021).

1.2.2 The approach

The paper's approach represents a scenario-based simple MCA, more precisely a non-formal version of a weighted sum analysis in a wider sense, as three infrastructure alternatives are evaluated using different criteria. The six previously presented socio-technical scenarios constitute the evaluation framework for the forward-looking implementation analysis (see Table 3). First, three key requirements per discipline and infrastructure option (3x4x3) were jointly identified in three semi-structured online workshops[1]. They describe discipline-specific require-

[1] In a semi-structured online workshop, three researchers from the disciplines of engineering, sociology and law were asked the following question. „*What are requirements that needs to be fulfilled according to your research findings to increase the chance of a successful implementation of the respective infrastructure option. Please name three requirements per infrastructure option*." The requirements and their definition were jointly developed and discussed. The workshop was moderated by the author who documented the discussion online and live to be able to develop a common understanding. After the workshop, the researchers got some days to finalize the definition of their requirements.

ments that need to be fulfilled to implement the respective infrastructure. Second, each researcher evaluated the chance of realization and the costs of their key requirement which let to 15 *implementation requirements* (criterion 1.1).

Table 3: Approach of the implementation analysis.

	Step	*Method*	*Result*
		Criterion 1.1: implementation requirements	
1	Definition of infrastructure options	Workshop-based identification key requirements	36 key requirements: • 9x sociological • 9x legal • 9x techno-economic • 9x economic
2	Assessment of key requirements	Expert opinion on key requirements	• 15 implementation requirements
		Criterion 1.2: future robustness	
1	Specification of infrastructure options	Identification of related key factors per key requirement	• 1-3 key factors per key requirement
2	Evaluation of infrastructure feasibility	Consistency analysis (key requirements and infrastructure options)	• 216 consistency values
3	Calculation of consistency scores	Interdisciplinary infrastructure evaluation, analysis	• 12 discipline-specific consistency levels • 4 option-specific consistency levels • 18 scenario-specific consistency levels

Source: Author's elaboration.

The evaluation of the future robustness (criterion 1.2) builds on the 36 key requirements. First, the 23 key factors were used to specify each key requirement. For each key requirement, 1-3 key factors are chosen which best represent the respective infrastructure. For a consistency analysis, the infrastructure options are translated into the language of the QSA, or to be more precise, in numerical terms. Second, the six socio-technical scenarios were used to assess whether the key requirement is consistent with a certain scenario, which results in 216 consistency values (36 key requirements x 6 scenarios). Finally, different aggregated consistency scores were calculated to assess the future robustness.

Table 4 describes the approach of the ambition analysis. It exceeds the German case study to assess the 1.5°C-alignment of the H2 infrastructures focusing on the energy carriers and related implications.

Table 4: Approach of the ambition analysis.

	Step	*Description*	*Focus*
		Criterion 2.1: Impact on the environment	
1	Comparison of green H2 and blue H2	• CO2 emissions • CH4 emissions • Consequences of CCS	Energy carrier
2	Discussion on green H2 and related infrastructure	Perspectives on green H2 • Economic • Sociological • Legal • Techno-economic	Implications for infrastructures
Criterion 2.1: Impact on the energy transition			
1	Calculation of 1.5°C-aligned emissions budgets	• Global CO2 budget • German CO2 budget	Emission constraints
2	Identification of potential risks related to investments in natural gas pipelines for retrofitting	• Lock-ins • Climate-related risks • Green finance gap	Retrofitting of existing pipelines or new pipelines for Green H2

Source: Author's elaboration.

To assess the *impact on the environment* (criterion 2.1), the emissions and environmental consequences along the whole value chain of green H2 compared to blue H2 are discussed. Additionally, four perspectives on green H2 provides insights on the required infrastructure design. To understand the *impact on energy transitions* (criterion 2.2), the emission budget associated with the 1.5°C-goal and risks related to investments in natural gas infrastructure for retrofitting are identified.

1.3 RESULTS

In this section, the results of the implementation and ambition analysis are represented. While analysing the criterion of feasibility (*implementation requirements* and *future robustness*) concentrates on Germany, investigating the 1.5°C-alignment (*impact on the environment* and *energy transitions*) is relevant for an international context.

1.3.1 IMPLEMENTATION ANALYSIS

1.3.1.1 CRITERION 1.1: IMPLEMENTATION REQUIREMENTS

Since it is unknown which possible future development will materialize, it is crucial to assess the future robustness of investment and policy decisions by considering different scenarios to the chance of implementation. In three discipline specific workshops, the author identified with the researchers from the disciplines of engineering, sociology and law, for each infrastructure three key requirements (4x3x3). This step is central for the interdisciplinary analysis. It brings together the disciplines' individual findings in a consistent way. All disciplines are weighted equally and transferred into a common qualitative format. Table 5 provides on overview of all key requirements. A description for all key requirements is available (for example see Table A.3 in the Appendix).

Table 5: Overview key requirements.

Disciple	***Option 1 (CO2 pipelines)***		***Option 2 (retrofitting & admixture)***		***Option 3 (new H2 pipelines)***	
law	1.1	Removal of CO2 export ban	2.1	Cost allocation of blue H2 production	3.1	Legal regime for H2 pipelines
	1.2	Timely CO2 network implementation	2.2	Clarification of gas definition	3.2	Non-discrimination of blue H2
	1.3	Legal framework for CO2 networks	2.3	Coordination of gas quality	3.3	H2 tariffs regulations
sociology	1.4	CCS with industrial applications & BECCS	2.4	Acceptance of pipeline retrofitting	3.4	Acceptance of H2 pipelines
	1.5	Acceptance of CO2 Pipelines	2.5	Synergies with renew. energy systems	3.5	Synergies with renew. energy systems
	1.6	Acceptance of CCS	2.6	Acceptance for H2	3.6	Acceptance of H2
Economics	1.7	Dominance of fossil fuels	2.7	Competitiveness of H2	3.7	Governmental market incentives
	1.8	Business models for CO2 transport and storage	2.8	H2 demand for admixture	3.8	High demand for H2
	1.9	Incentives for carbon capture	2.9	Supply for H2 admixture	3.9	High supply for H2
engineering	1.10	Future perspective for CO2 capture	2.10	Incentive to inject H2	3.10	Competitiveness of H2 technologies
	1.11	Low-cost CO2 pipelines	2.11	Constant H2 admixture <30%	3.11	Low-cost H2 pipelines
	1.10	CO2 transport scaling-effects	2.12	Investments in pipeline retrofitting	3.12	Infrastructure synergies via industry hotspots

Source: Author's elaboration.

The engineering workshop revealed, that there are no purely technical key requirements. The sociological key requirements indicate that the source of H2 is essential for the acceptance of H2 in general. The key requirement *1.4 CCS with industrial application and BECCS*[2] implies

[2] Bioenergy with carbon capture and storage.

that CCS is more accepted when applied to renewable energy generation (see Schönauer and Glanz 2021).

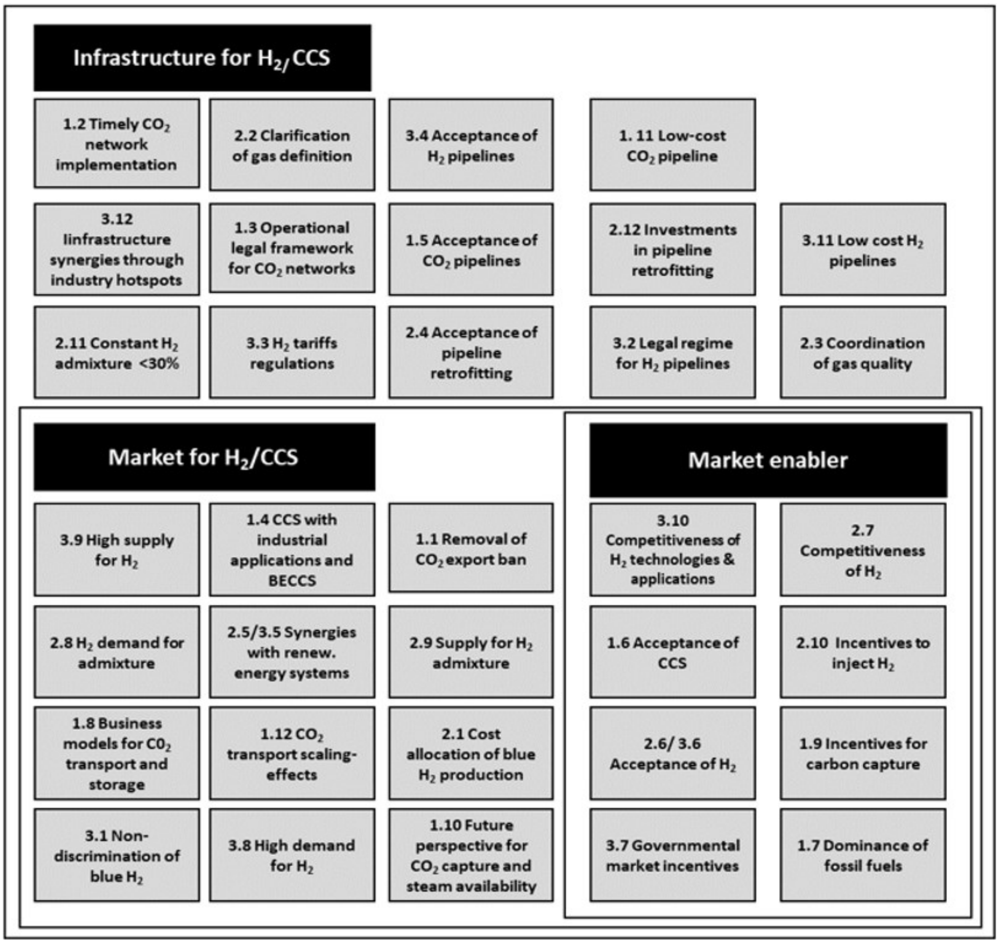

Figure 2: Key requirements and system levels.
Source: Author's elaboration.

Additionally, the analysis revealed that the key requirements address different system levels, namely *infrastructure for H2/CCS*, *Market for H2/CCS* and *Market enabler* (see Figure 2). It demonstrates that the feasibility of a H2 infrastructure does not only depend on infrastructure aspects but also on the establishment of a H2 economy. These results underline the importance to include different discipline's findings and the big picture perspective. Economic key requirements e.g. do not refer to *infrastructure for H2/CCS*, while the legal key requirements do not address *market enabler.* The sociological key requirements refer to all three levels, which shows that neglecting social factors would leave a knowledge gap on all levels.

To distil the implementation requirements, which represent crucial key requirements, each researcher evaluated the chance of realization and costs of their identified key requirements (skala low-medium-high). Table 6 exemplarily displays the results for infrastructure option 3.

Table 6: Stakeholder and feasibility assessment of infrastructure option 3.

#	Key requirements	Discipline	Realization	Costs	#7	#8	#15	#21	#22
3.1	Legal regime for H2 pipelines	law	high	medium			x		x
3.2	Non-discrimination of blue H2	law	medium	low					x
3.3	H2 tariffs regulations	law	high	low			x	x	x
3.4	Acceptance of H2 pipelines	sociology	medium	high	x	x			x
3.5	Synergies with renew. energy systems	sociology	high	low	x	x	x	x	x
3.6	Acceptance of H2	sociology	high	low	x	x			
3.7	Governmental market incentives	economics	high	high					x
3.8	High demand for H2	economics	medium	medium	x			x	x
3.9	High supply for H2	economics	high	medium				x	x
3.10	Competitiveness of H2 technologies & applications	engineering	medium	medium			x	x	x
3.11	Low-cost H2 pipelines	engineering	medium	medium	x	x		x	x
3.12	Infrastructure synergies via industry hotspots	engineering	high	low			x	x	
	#7: Citizens, #8: Public interest groups, #15: Economic lobby groups, #21: Investors in gas sector, #22: Political decision-makers								

Source: Author's elaboration.

According to the evaluation, requirements that support or hinder the implementation were differentiated. While *supportive* implies a high chance of realization, *hindering* refers to a low chance. The costs display the effort that needs to be taken to realise the requirements. Three types of implementation requirements revealed to be crucial: low-cost supportive requirements, high-cost supportive requirements and high-cost hindering requirements. There were no low-cost hindering requirements.

As Figure 3 shows, there are 15 implementation requirements. The great majority (10 out of 15) represents drivers (supportive implementation requirements). This result can be interpreted as a positive sign for the feasibility of H2 infrastructure in Germany. 90% of the supportive implementation requirements refer to option 2 and 3. 4 out of 5 hindering requirements refer to option 1. The majority of supporting low-cost requirements are sociological in nature and refer to option 2 and 3. While no techno-economic implementation requirements were categorised as hindering, 3 out of 5 hindering factors are economic factors and apply to option 1 and 2.

One example is *1.8 Business models for CO2 transport and storage*. As storage of CO2 is legally not possible in Germany (Deutscher Bundestag 2018), CCT is facing high barriers. Even if the public acceptance for CCS (*1.6 Acceptance of CCS*) would increase, and the export of CO2 would be possible (*1.1 removal of CO2 export ban*), business options for cross-border CO2 transport and storage are needed. Additional questions arise: Will CO2 be sold as a good or as a waste product? Who is responsible for CO2 leaks from the pipelines or storage sides? Is sufficient storage capacity available? The development of a market for related services at decent costs and adequate conditions seems very low. These questions are also relevant for option 2, as CCTS is also needed for blue H2.

Similarly, adequate *2.8 H2 demand for admixture,* which is relevant for option 2, seems rather low. H2 is regarded as a scare commodity (SRU 2021a). To realize option 2, a constant admixture of H2 into the natural gas network would be required (*2.1 Constant H2 admixture <30%).* Multiple injection points or a separate H2 network which functions as a backbone would be needed. Therefore, it is necessary that suppliers of H2 provide the required amount of H2 (see *2.9 Supply for H2 admixture*). The availability of H2 depends on the price for H2 admixture, which is determined also by the demand for H2 admixture. Since there are disadvantages of H2 compared to natural gas in the EU ETS (3.2 *Non-discrimination of blue H2*), the demand for admixture seems rather low. This example demonstrates the value of the interdisciplinary approach. Without identifying different requirements, the understanding of this barrier would remain incomplete.

3.7 Governmental market incentives represent an economic supportive high-cost requirement. To realize option 3, a high level of H2 demand (see key requirements 3.8) and a high level of H2 supply (see key requirements 3.9) are essential. National H2 strategies and corresponding taxes or requirements, such as standards related to the EU Taxonomy can boost the developments. Considering the German and European H2 strategies and related subsidies, the chance of realization is high, while the costs are also high.

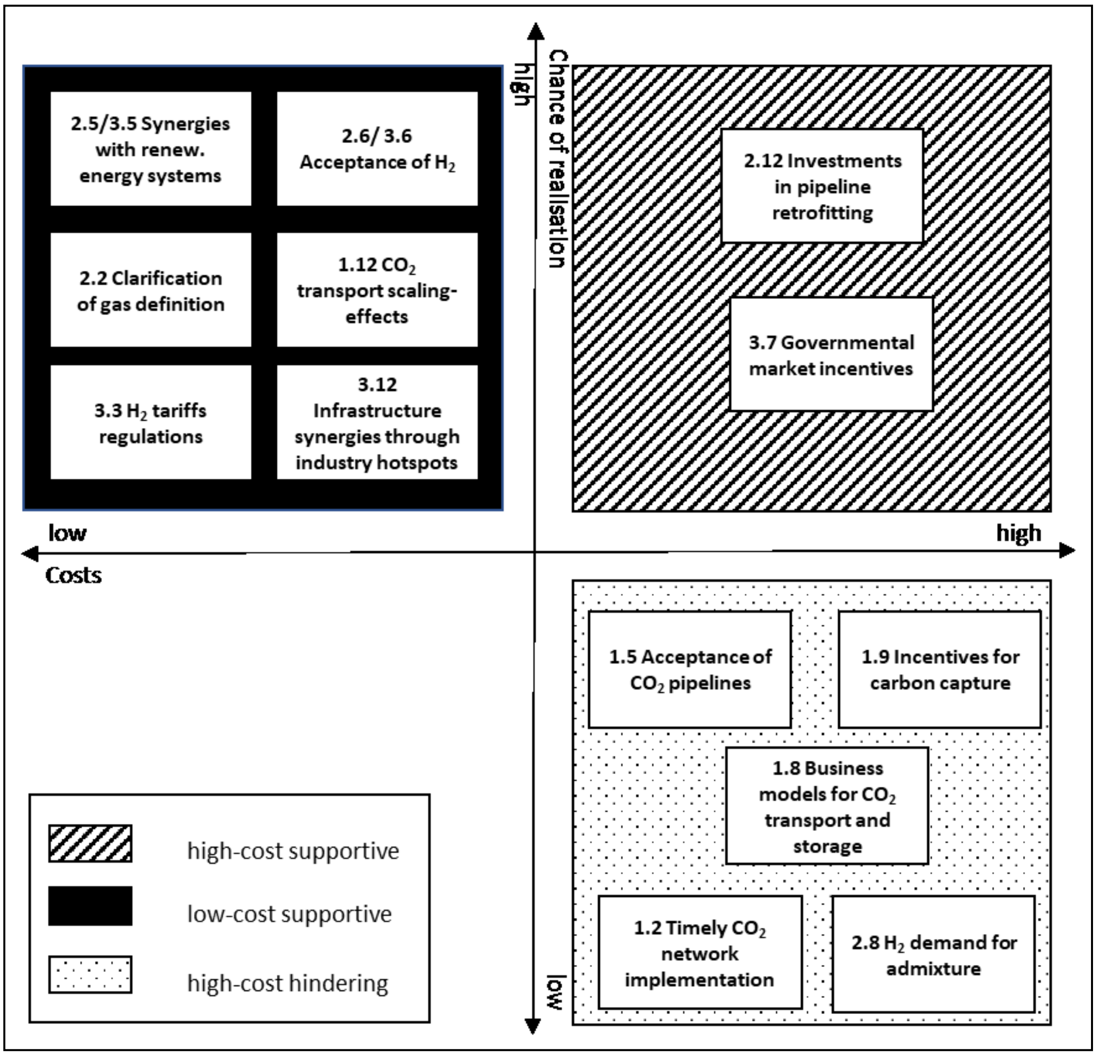

Figure 3: Implementation requirements.
Source: Author's elaboration.

1.3.1.2 CRITERION 1.2: FUTURE ROBUSTNESS

The qualitative key requirements were translated into quantitative and comparable consistency scores to assess the future robustness. The author conducted a consistency analysis. For each key requirement, the consistency with each scenario was assessed resulting in total of 216 individual consistency scores (6 scenarios x 36 requirements). The consistency analyses for option 2 can be found as an example in the Appendix (see Table A.4). For the robustness check, the consistency values were aggregated.

Table 7 shows the different consistency values for each infrastructure option (average overall consistency), for each scenario (overall consistency) and for each discipline (average consistency). The discipline-specific values represent the average value of the three key requirements' consistency.

Table 7: Infrastructure future robustness check.

Scenarios	*Overall consistency*	*law*	*sociology*	*economics*	*engineering*
Option 1 (CO2 pipelines for CCT)					
(1) Fossil revival instead of green progress	2.3	2.7	1.3	3.0	2.0
(2) Technology-open green transformation	4.1	4.7	4.3	3.3	4.0
(3) Green transformation with hydrogen	4.0	4.7	4.0	3.0	4.3
(4) Incremental green transformation	2.5	2.3	2.3	2.3	3.0
(5) Top-down effort & conflicting interests	2.8	3.7	3.3	2.0	2.3
(6) Bottom-up effort & political inaction	2.3	2.7	2.7	1.7	2.3
Average	**3.0**	**3.4**	**3.0**	**2.6**	**3.0**
Option 2 (gas pipeline reuse and admixture)					
(1) Fossil revival instead of green progress	1.3	1.0	1.7	1.0	1.3
(2) Technology-open green transformation	4.5	4.3	5.0	4.7	4.0
(3) Green transformation with hydrogen	4.8	5.0	4.7	5.0	4.7
(4) Incremental green transformation	3.0	2.7	4.0	2.3	3.0
(5) Top-down effort & conflicting interests	3.7	4.3	3.3	3.7	3.3
(6) Bottom-up effort & political inaction	3.2	2.3	3.7	3.3	3.3
Average	**3.4**	**3.3**	**3.7**	**3.3**	**3.3**
Option 3 (new H2 pipelines)					
(1) Fossil revival instead of green progress	1.2	1.0	1.7	1.0	1.0
(2) Technology-open green transformation	4.7	4.7	4.7	4.7	4.7
(3) Green transformation with hydrogen	4.9	5.0	5.0	5.0	4.7
(4) Incremental green transformation	3.2	2.7	4.0	3.3	2.7
(5) Top-down effort & conflicting interests	3.6	4.3	3.0	4.0	3.0
(6) Bottom-up effort & political inaction	3.6	2.3	3.7	4.3	4.0
Average	**3.5**	**3.3**	**3.7**	**3.7**	**3.3**

Source: Author's elaboration.

Considering all scenarios, the average overall consistency values generated for each infrastructure reveal that option 3 (*new H2 pipelines*) is most consistent (3.5). A positive consistency of 3.5 implies that option 3 is the most feasible infrastructure compared to option 2 (3.4) (*reuse and admixture*) and option 1 (3.0) (*CO2 pipelines for CCT*). Notably, the difference between option 2 and 3 is very small, while the difference to infrastructure option 1, *CO2 pipelines for off-shore CCS*, is bigger. Option 1 was identified to be the least feasible option. To be more precise, a value of 3 implies for option 1 that it is unclear whether a CO2 infrastructure is positively or negatively consistent and, thus, feasible or not.

Looking at the different scenarios, all options are most consistent and thus feasible with either scenario 2 and 3 - the two green transformation scenarios - in terms of the overall consistency level. It means that scenario 2 and scenario 3 have the highest overall consistency values, which is greater than or equal to 4. While the highest overall consistency level (4.9) results from option 3 with scenario 3 – *green transformation with H2*, the lowest overall consistency level (1.2) refers to option 3 with scenario 1, the fossil-dominated scenario. Considering the relevant stakeholders, *political decision-makers (#22)* are the most involved and thus important stakeholder group, followed by *citizens & society (#8)* and *investors (#21*). *Economic lobby groups (#15)* are the least relevant. *Political decision-makers* are relevant for 83% of all key requirement and all legal requirements.

In sum, the implementation analysis identified option 1 (CCT) as the least feasible with regards to both the *implementation requirements* (criterion 1.1) and the *future robustness* (criterion 1.2). In comparison to option 2 (retrofitting & admixture) and option 3 (new H2 pipelines), the most hindering and the least fostering implementation requirements apply to option 1. Option 1 shows also the lowest future robustness, as the overall consistency is the lowest over all scenarios. Therefore, option 1 is ruled out of further considerations. In the case study context, Option 2 and 3 seem rather feasible if certain conditions are met. Both options show more fostering (option 2: 4x, option 3: 45) than hindering (option 2: 1x, option 3: 0) implementation requirements and a high future robustness in form of a high overall consistency (option 2: 3.4 option 3: 3.5). However, a differentiation between option 2 and 3 is not possible within the case study. Information on the role of different types of H2 is missing. Where and for what applications H2 will be used, is unknown as well. Therefore, the following ambitions analysis exceeds the case study and examines which feasible infrastructure option is 1.5°C-alinged.

1.3.2 AMBITION ANALYSIS

1.3.2.1 CRITERION 2.1: IMPACT ON THE ENVIRONMENT

The environmental impact of infrastructures is primarily determined by the energy carrier, and thus the distinction between fossil-based and renewable H2. The GHG emissions along the lifecycle of renewable H2 produced through electrolysis with renewable energy are close to zero (IEA 2019b; SRU 2021b). Compared to other types of H2, only renewable H2 is sustainable in the long run (SRU 2021b; BMWi 2020).

Although blue H2 is considered a low-carbon energy carrier due to the use of CCS technologies, it is not without emissions and environmental consequences. While the CO2 emissions from production of H2 from natural gas and CCS (30-120 $gCO2_{eq/}$ KWhH2) are lower compared to alternative fossil sources such as coal (570 $gCO2_{eq/}$ KWhH2) or natural gas without CCS (300 $gCO2_{eq/}$ KWhH2), renewable H2 has close to zero CO2 emissions (SRU 2021b). Besides CO2 emissions, blue H2 has a high climate impact considering all emissions along the entire lifecycle. These emissions also comprise methane (CH4) emissions of natural gas (Howarth and Jacobson 2021). As CH4 has an up to 87 times higher global warming potential than CO2 in the first 20 years (Myhre et al.), CH4 emissions should not be neglected. Direct CH4 emissions are caused by natural gas extraction, transport and storage through leakages or intentional flaring and venting. These emissions are often not fully considered (Cremonese and Gusev 2016) and underestimated due to measuring difficulties (MacKay et al. 2021; Schwietzke et al. 2016). Same counts for fugitive CO2 emissions during capture, transport and storage (SRU 2021a).

Additionally, CCS has consequences for the environment and humans (salination of ground water or health risks due to CO2 accidents) (Howarth and Jacobson 2021). The process of CCS requires additional energy (Zhou et al. 2021). Under current law, carbon storage is not allowed in Germany (Deutscher Bundestag 2018), which requires a change of law or storage abroad. It is far from clear, if there will be sufficient and safe international storage capacities at a decent price (SRU 2020). For a significant emission reduction, large scale CO2 storage capacities need to be identified in a short time on a global scale, which increases the risk of handling and operating failure. Ethically, carbon storage requires monitoring for hundreds of years, as CO2 should remain captured *forever*, which places a huge burden on future generations (Steigleder 2017).

Renewable H2 is also not without consequences. To avoid negative consequences of electrolysis associated with the high demand for water, regulations for an efficient use of water and the withdrawal of surface and ground water is advisable to, e.g., guarantee supply of drinking water (SRU 2021a).

In sum, renewable H2 is preferable over blue H2 from an environmental perspective, which is why H2 infrastructure should be adjusted to renewable H2 exclusively. Table 8 highlights different perspectives on renewable H2 and provides determinants for a related infrastructure. Although green H2 is expected to become cheaper than blue H2 in the near future (Noussan et al. 2021), it will remain scarce. As the demand cannot be satisfied with green H2 from Germany, imports are needed. Consequently, green H2 is too valuable for admixture into the natural gas grid. It should only be used in hard-to-abate sectors, such as the steel or cement industry, where a decarbonisation through the more efficient electrification is not possible. A broad usage of green H2 outside the industry sector, for example for individual mobility, is not advisable. The industry requires mainly pure H2. Pipeline retrofitting for less than 100% H2 is thus not suitable for these industries and green H2. As long as the import amounts, routes and the application of H2 are uncertain, a step-by-step infrastructure starting with demand-oriented micro-grids seems advisable (SRU 2021a). The question remains if these micro-grids should consist of new H2 pipelines or be created by retrofitting of gas pipelines, which will be addressed in the following.

Table 8: Perspectives on renewable H2 and related infrastructure.

Perspective	***Arguments***
Economic	• **H2 availability:** Demand for green H2 exceeds the current and future German supply and requires imports • **Cost-effectiveness**: As a scarce resource, H2 is not suitable for admixture into the natural gas grid and should only be used in hard-to-abate sectors • **H2-trade:** Germany will decrease fossil fuel dependencies, but remain dependent on H2 import, preferable from neighbouring countries to avoid geopolitical conflicts • **Transition risk:** Demand-oriented pipeline projects reduce the economic risk of asset stranding
Socio-logical	• **Acceptance:** Social acceptance of hydrogen is higher when it supports energy transition and renewable energies • **Standards:** To not export emissions and guarantee human rights along the value chain, standards for green H2 are needed
Legal	• **Energy law:** There is no difference between fossil-based and renewable hydrogen under current German energy law • **Climate protection law:** Green H2 can make a contribute to GHG neutrality • **Renewable Energy Act (EEG):** The exemption from EEG surcharge for green H2 production helps to increase the competitiveness compared to blue H2
Techno-economic	• **Production**: For green H2, renewable energies are needed and thus capacity building, as well as the availability of suitable water resources • **Operation of electrolysis**: Cost-efficient production of H2 through electrolysis operating in a system serving way, geographically close distance to larger costumers, such as industry clusters • **Efficiency:** Electrification is most effective for decarbonisation, as the direct use of renewable energy is more efficient comparted to H2 or PtX technologies

Source: Author's elaboration.

1.3.2.2 Criterion 2.2: Impact on the energy transition

For a compatibility with the Paris Agreement, the global remaining CO2 budget guides national climate protection and energy transitions. The IPCC (Rogelj et al. 2018) calculated a remaining

CO_2 budget for the well below 2°C-target of 800 $GtCO_2$ from 2018 on (<1.75°C, 66.6% probability). Meeting the 1.5°C-target with a 67% probability translates into 420 $GtCO_2$ from 2018 on (Rogelj et al. 2018). Different approaches of how to allocate national budgets exist and have intra- and intergenerational justice implications (Helmholtz Climate Initiative 2020). The *equal-per-capita approach* uses Germany's share of world population (1.1%) and neglects historical emissions. It leads to a German budget of 6.7 $GtCO_2$ (≤1.75°C, 67% probability) respectively 4.2 $GtCO_2$ (≤1.5°, 50% probability) (SRU 2020). From a risk perspective, the 1.5°C-target and a conservative budget calculation are advisable, as new findings might indicate an even smaller budget (IPCC 2021).

The German 1.5°C-emission-budget will be used up between 2032 and 2035 depending on the rate of emission reduction (Kobiela et al. 2020). It implies that significant emission reduction is needed, which makes an natural gas exit unavoidable (Hirschhausen et al. 2020). Investments in natural gas have long-term implications for climate goals (Gürsan and Gooyert 2021). Kemfert et al. (2022) show that the expansion of natural gas infrastructure is a serious risk to energy transitions. Following this line of argumentation, investments in gas pipelines for future retrofitting for H_2 admixture entail multiple risks.

Firstly, investments in fossil supply chain, such as energy infrastructure, can cause carbon lock-ins. Fossil fuel dependencies and related emissions can become locked-in, as they determine developments for decades and can self-enforce barriers for energy transitions (Erickson et al. 2015). While studies warned of carbon lock-ins (Seto et al. 2016; Unruh 2000), fossil natural gas lock-in is becoming particularly relevant (Brauers et al. 2021; Powers 2021) and is amplified by investments in energy infrastructure (Fisch-Romito et al. 2021). Energy infrastructure lock-ins relate to the long technical life span of infrastructure. It is difficult and expensive to turn fossil infrastructure "green" and escaping path dependencies (Hafner et al. 2021). Investments in natural gas infrastructure thus create technological lock-ins by establishing technological systems comprising the whole value chain of energy (Powers 2021). It can also cause institutional (delay natural gas exit), behavioural (demand side) or discursive lock-in (misleading transition fuel narrative) (Brauers et al. 2021).

Secondly, investment in natural gas infrastructure can lead to climate-related risks, which are due to extreme weather events (physical risks) or policies accompanying net-zero transitions (transition risks) (Batten et al. 2016). Fossil asset stranding is regarded as a key transition risk (Caldecott et al. 2016) and a main challenge for energy transitions (Löffler et al. 2019). Physical fossil asset stranding from investments in the fossil industry and fossil energy infrastructure (Sen and Schickfus 2020) are particularly relevant. Climate policies impose limits to the use of fossil natural gas and infrastructure (McGlade and Ekins 2015). Consequently, investments in natural gas infrastructure might strand and miss expected profits even before retrofitting might occur (Tong et al. 2019). Mercure et al. (2021) estimate that half of the global fossil fuel asset could strand by 2036 in a net-zero scenario. According to the IEA (2021), $90 billion of coal and gas capacities could strand by 2030 ($400 billion by 2040). Tong et al. (2019) calculate that emissions from existing and planned energy infrastructure might exceed the entire 1.5°C-emission budget. Despite the need for a significant reduction of fossil gas consumption by 2030, Europe is planning fossil natural gas infrastructure for €18 billion (only pipelines).With these increasing investments, the EU risks a lock-in of future emissions and €87 billion stranded natural gas asset (including LNG Terminals) (Inman et al. 2021). Fossil-asset stranding leads to significant losses for investors as well (Semieniuk et al. 2022). Hickey et al. (2019) rightly ask the question whether gas networks have a future in a low-carbon energy system. Investments in natural gas infrastructure for future retrofitting for H2 are a serious economic risk.

Investment in natural gas infrastructure for future retrofitting, might imply a third risk regarding the green-finance-gap. Significant emission reduction requires massive investments in renewable energy and infrastructure (Hafner et al. 2021). The green finance gap describes the fact that despite the availability of financial capital, investors hesitate to invest due to planning insecurity (Polzin and Sanders 2020; Yoshino et al. 2019). Since the risk of energy asset stranding is underestimated (Caldecott et al. 2016) and investments in fossil infrastructure still increase, the green finance energy gap might even enlarge. Capital invested in fossil energy assets cannot be invested in renewable energy systems. Climate-related risks might potentially trigger a next financial crisis, as finance authorities warn (Monasterolo et al. 2017; Semieniuk et al. 2021). Low-carbon investment are difficult in times of financial instability, which puts energy transitions at risk (Kemfert and Schäfer 2012). Fossil divestments can reduce the risk of delaying energy transitions. In sum, building new pipelines instead of investing in gas pipelines for future retrofitting is preferable from an economic and transition view.

1.4 Discussion

In this section, key insights and limitations are discussed (section 3.4.1). Recommendations for decision-makers are drawn in the light of the cooperation problem of establishing a H2 economy (section 3.4.2).

1.4.1 Key insights and limitations

Table 9 provides an overview of the key results. Option 1 (decentral decarbonisation with CCT) revealed to be the least feasible infrastructure option both with respect to the implementation requirements (least fostering and most hindering requirements) and the future robustness (ordinal overall lowest consistency). Therefore, Option 1 was excluded from the ambition analysis, which shows that new pipelines for green H2 (Option 3) are the most feasible and 1.5°C-aligned option. This is because blue H2 has a worse climate impact than green H2 and because investments in natural gas pipelines for future retrofitting (Option 2) imply serious risks for energy transitions.

Table 9: Overview – results

Criteria	***Focus***	***Result***
1.1 Implementation requirements	Case study: critical requirements	Option 1: 3x hindering, 1x fostering Option 2: 1x hindering, 4x fostering Option 3: 0x hindering, 5x fostering
1.2 Future robustness	Case study: requirements over different scenarios	Overall consistency (ordinal): option 1 (3.0)<option 2 (3.4)<option 3 (3.5)
2.1 Impact on the environment	Type of hydrogen: blue H2 vs. green H2	GHG (CO2, CH4): blue H2 > green H2 Consequences: CCS > electrolysis
2.2 Impact on energy transitions	Infrastructure for green H2: retrofitting vs. new pipelines	Risks related to retrofitting: lock-ins, stranded assets, green energy finance gap

Source: Author's elaboration.

Concerning the implementation requirements of the H2 infrastructure, no purely technical but only techno-economic requirements were identified. This interesting finding is in line with the paper's understanding of feasibility, which defines technical feasibility as a necessary, but insufficient precondition for a successful implementation. The feasibility analysis revealed the need to assess the 1.5°C-alignment as an additional criterion, which is confirmed by Tong et al. (2019) who show that emissions from existing energy infrastructure is a risk for the 1.5°C-goal. The paper comes to a similar conclusion as Ogden et al. (2018), who find that H2 blending into the natural gas grid is not advisable and that dedicated pipelines for green H2 are needed. However, the reasoning differs. While they refer to a limited emission reduction potential due to technical difficulties of separating green H2 from the blend, the paper shows that it does not make economic sense to blend in green H2, as it is too scarce and valuable. The paper's findings add a new perspective on the question of repurposing parts of the natural gas grid or building new H2 pipelines. While Cerniauskas et al. (2020) show that the former has significant cost advantages over the latter, which might boost H2 infrastructure development in the short run, the paper reveals that investments in pipeline retrofitting might hinder the energy transition in the long run.

These findings are significant for science and decision-makers. The study demonstrates that considering multiple perspectives leads to new scientific results that differ from those of a single discipline and that better capture the complexity of establishing a H2 economy. Further, the study provides guidance for decision-makers on the timely issue of decarbonizing with H2 in the closing window of limiting global warming.

One main limitation of this paper is the subjectivity of expert judgements related to the evaluation of implementation requirements and future robustness. It could be that different experts have different opinions leading to different individual results. The issue goes back to the philosophy of science question of how to treat uncertainty of future developments with respect to informing decision-makers on climate mitigation.

From a methodological perspective, future developments characterized by deep uncertainty are unpredictable. To forecast if and with what probability the requirements will be met in different future scenarios is not possible. There is a discrepancy between the need of decision-makers for precise statements about the future and the methodological limits of science. If scientists do not provide judgement about the future, there will be judgments anyway that may be inaccurate compared to those of science. If scientists provide suitable judgements about the future, it can hardly fulfil the need for truth and security about the future or lead to a false perception of knowledge about the future.

In the light of the science-practice discrepancy, expert judgments are suitable for the paper's goal and commonly used in climate policy. Ho et al. (2019), e.g., even provide subjective probabilistic judgment about different climate scenarios. To increase the quality of expert judgements and to avoid information asymmetries, researchers from the case study team were invited, who know the infrastructure options and were involved in the scenario development. To provide a differentiated picture and increase transparency, the experts evaluated multiple aspects related to their research instead of assessing the infrastructures as a whole. The impact of subjectivity to the overall findings is rather minor, as the expert options are one component of a comprehensive analysis. The key findings depend on the analysis as a whole. Similar to the aim of scenario analysis, the study targets to stimulate decision-makers to think in a holistic way. The subjectivity of expert opinions does not conflict with this aim.

1.4.2 Recommendations in the light of the coordination problem

New pipelines for renewable H2 have been found to be both feasible and 1.5°C-aligned. As displayed in Figure 4, main recommendations for investors are that new H2 pipelines should be build (1) demand-oriented and step-by-step, (2) starting with a micro-grid for an industry clusters in minimal distance to production. (3) H2 pipeline planning should linked to gas and energy network development plans and the national GHG budget.

To define what is necessary to put the H2 pipelines into practice exceeds the scope of the paper. These decisions relate to a three-fold chicken and egg problem of establishing a H2 economy and coordinating infrastructure, H2 demand and supply. A H2 infrastructure is necessary for enabling trade. Potential suppliers will hardly offer H2 without a sufficient demand and suitable transport options. To turn potential demand for H2 into binding purchasing decisions, information on available amounts, prices and transport is required. Investments in infrastructure depend on expected demand, supply and geographical planning. Without a decent price and supply guarantee, there will hardly be binding purchase agreements. For the production of green H2, the costs and availability of renewable energy and water, but also the technical maturity of electrolysis are crucial. It shows that H2 infrastructures need to be considered in the context of a H2 economy.

Therefore, recommendations on supply and demand aspects are offered based on SRU (2021a). While infrastructure related recommendations are meant for investment decisions of economic actors, those on supply and demand are directed towards political decision-makers. The differentiation is because economic actors build and operate energy infrastructure, whereas governments indirectly influence the developments by setting framework conditions.

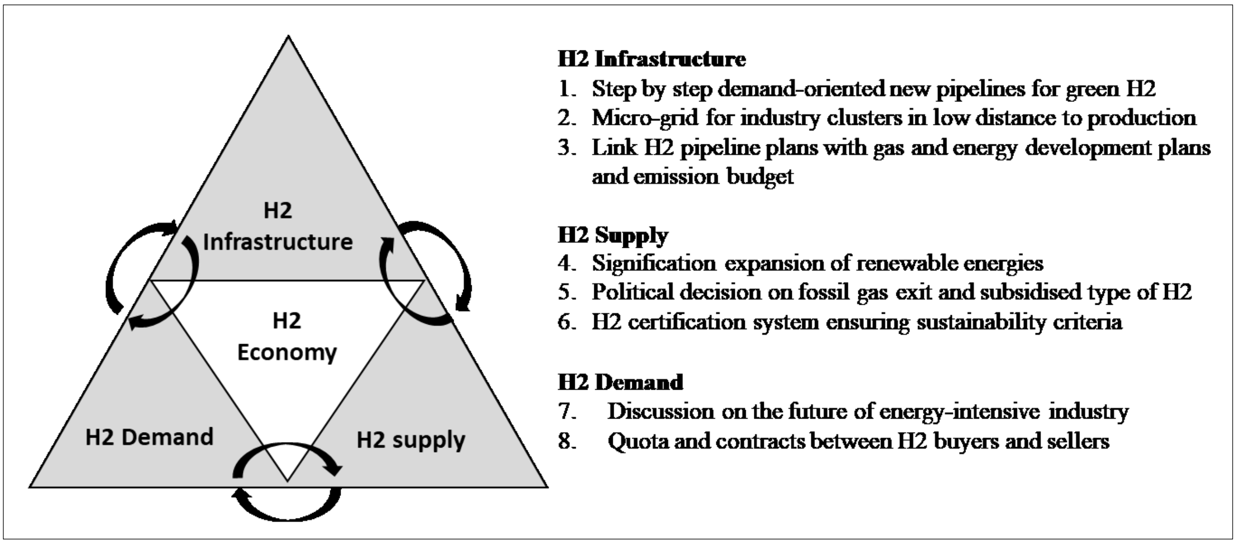

Figure 4: Recommendations in the light of the H2 coordination problem.
Source: Author's elaboration based on SRU (2021a).

1.5 Conclusion

The aim was to evaluate three H2 infrastructure options in terms of *(1) feasibility* and *(2) 1.5°C-alignment* to inform investment and political decisions. Pipeline infrastructures, that are feasible but not in line with climate goals, are problematic from a micro- and macro-perspective leading to economic risks and a delay of energy transitions. The same applies for 1.5°C-aligned infrastructures, which are not feasible. To assess the two criteria, an implementation analysis and an ambition analysis were combined. As methodological contribution, the author offers a new approach that triangulates *qualitative scenario analysis* and a non-formal, simple *multi-criteria-decision-analysis* to include (i) research from different disciplines and (ii) different socio-technical scenarios to allow for a holistic economic infrastructure assessment.

The implementation analysis revealed that the chances for a successful H2 infrastructure implementation are rather high in Germany. The author identified high-cost supportive requirements, such as *governmental market incentives* (economic), low-cost requirements such as *acceptance of H2* (sociological), or *synergies through industry hotspots* (techno-economic). These findings were not been possible with a single discipline's perspective. It highlights the value of interdisciplinary approaches for studying socio-technical transitions. *Decentral decarbonisation with CCT* (option 1) proved to be less feasible compared to *retrofitting of gas pipelines for admixture* (option 2) and *new H2 pipelines* (option 3).

Evaluating the impact on the environment and on energy transitions for the ambition analysis showed that the origin and application of H2 is decisive. Since only renewable H2 is sustainable, but scarce, admixture into the natural gas grid is not advisable for efficiency and economic reasons. Additionally, blue H2 is not without emissions and environmental consequences. Thus, focusing on green H2 is advisable, leaving the question of reusing gas pipelines or building H2 pipelines. The analysis revealed that investments in the gas grid for future retrofitting carry the risk of delaying the energy transition through lock-ins and fossil asset stranding.

Thus, the research question - *What is a feasible and 1.5°C-aligned H2 infrastructure for Germany?* - can be answered as follows: New H2 pipelines (option 3) for renewable H2 is the most feasible and 1.5°C-aligned option. The main recommendation for investments is to construct new H2 pipelines demand-oriented step-by-step, starting at industry clusters with small distance between buyers and electrolysis.

Details for future pipelines for renewable H2 are uncertain and relates to the challenges of establishing an H2 economy: As a threefold chicken-egg-problem, supply, demand and infrastructure need to be coordinated under planning insecurity. It requires to include the bigger picture for energy transition decision-making. The analysis revealed that *decarbonisation* of the energy systems inevitably implies a defossilisation and requires a fossil natural gas exit. Efficiency and sufficiency measures can support the defossilisation. The less energy is needed, the easier it gets to provide the required infrastructure and energy while staying within the remaining emission budget.

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APPENDIX

Table A.1: Overview of key factors

Categories	*Key Factors (number)*
Outcomes	Realization of National Climate Goals (1)
Stakeholders	Investors in Gas-Related Technologies (21) Character of Public Policy (22) Power of Lobbyism (15) Influence of Public Interest Groups (8) Behaviour & Public Acceptance (7)
Measures	Phase Out & Phase In: Fossil & Renew. Gas (2) Cost of Carbon (4) Carbon Capture Technologies (12) Lignite Energy Phase Out (17) Governmental Support for Transformation Technologies (23)
Sector-specific Developments	Fuel of Road Traffic (9) Heating (18) German Production of H2 (11) H2 Power Plants (19) Technological Progress & Market Maturity (20)
Infrastructure Developments	Electricity Network Expansion (5) Gas Network Expansion (14)
Energy-related Developments	Electricity Production (6) German Gas Demand (10) Import of H2 (16) Electricity Consumer Price (13) natural gas Price (3)

Source: based on (Hoffart et al. 2021).

Table A.2: Key factor-based relevant stakeholders.

Stakeholder Groups	*Key Factors (number)*
Citizens	Behaviour and Public Acceptance (7)
Public interest groups	Influence of Public Interest Groups (8)
Economic lobby groups	Power of Lobbyism (15)
Investors in gas sector	Investors in Gas-Related Technologies (21)
Political decision-makers	Character of Public Policy (22)

Source: based on (Hoffart et al. 2021).

Table A.3:Key requirements for infrastructure option 1

Option 1: CCT Infrastructure			
#	*Key requirement*	*Discipline*	*Explanation*
1.1	Removal of CO2 export ban	law	To enable CO2 export for off-shore CCS, a provisional application of the 2009 amendment to the London Protocol in Germany and the Netherlands and collaborations are required.
1.2	Timely CO2 network implementation	law	CO2 pipelines have to be planned, permitted and constructed before operation. Especially the planning process and the permitting procedure can be lengthy due to lacking experience.
1.3	Operational legal framework for CO2 networks	law	The legal framework to specific challenges of CO2 pipeline networks on EU and national level has to be adjusted: coordination of CO2 stream quality, harmonisation of legal requirements, safety ordinance.
1.4	CCS with industrial applications and BECCS	sociology	Acceptance of CCS related to fossil energy carrier is low. CCS with industries and BECCS is more accepted. To increase acceptance and decrease the risk of protests, CCS should not be used to decarbonise fossil fuel, especially coal power plants.
1.5	Acceptance of CO2 pipelines	sociology	Feasibility of CCS requires acceptance of related pipelines. For acceptance, security and insurance issues as well as options for participation are important.
1.6	Acceptance of CCS	sociology	Acceptance of CCS is required and depends also on the opinion of stakeholders from civil society, which enjoy a high level of trust (e.g. NGOs, civil association).
1.7	Dominance of fossil fuels	economics	Big (industrial) emitters still need to rely on fossil fuels and energy. A shift to renewable energy and fuels makes carbon capture obsolete.
1.8	Business models for CO2 transport and storage	economics	A market that offers cross-border CO2 transport and storage at affordable costs and adequate conditions is required.
1.9	Incentives for carbon capture	economics	To incentivise carbon capture, related costs need to be smaller than the costs of CO2-emissions. Besides the costs of emission certificates, the electricity price is important.
1.10	Future perspective for CO2 capture and steam availability	engineering	For investment in CCT technologies, a long-term usage is essential. The costs of carbon, electricity and resources determine the economic feasibility. Steam needs to be available locally at low costs.
1.11	Low-cost CO2 pipelines	engineering	For CO2 transport to be economically attractive, costs for new CO2 pipelines are important. To reduce costs of CO2 pipelines, multiple booster stations allow for a lower diameter, which is cheaper.
1.12	CO2 transport scaling-effects	engineering	To decrease the costs of CO2 transport and to allow for synergies, local industry clusters aiming at joint CO2 transport are needed.

Source: Author's elaboration.

Table A.4: Scenario-based evaluation of infrastructure option 2.

#	***Key Requirements (related key factor)***	***S (1)***	***S (2)***	***S (2)***	***S (4)***	***S (5)***	***S (6)***
	discipline of law						
2.1	Cost allocation of blue H2 production (#4, #23, #3)	1	4	5	2	5	2
2.2	Clarification of gas definition (#22)	1	5	5	4	5	1
2.3	Coordination of gas quality (#23, #14, #15)	1	4	5	2	3	4
	discipline of sociology						
2.4	Acceptance of pipeline retrofitting (#7, Option for participation)	1	5	4	4	4	3
2.5	Synergies with renew. energy systems (#11, #6, #16)	2	5	5	4	3	4
2.6	Acceptance of H2 (#9, #18, #7)	2	5	5	4	3	4
	discipline of economics						
2.7	Competitiveness of H2 (#3, #4)	1	5	5	2	4	2
2.8	H2 demand for admixture (#2, #10, #14)	1	4	5	2	4	4
2.9	Supply for H2 admixture (#16, #11, #4)	1	5	5	3	3	4
	discipline of engineering						
2.10	Incentive to inject H2 (#2, #3, #10)	2	4	5	3	4	2
2.11	Constant H2 admixture <30% (#11, #14, #16)	1	4	5	2	2	4
2.12	Investments in pipeline retrofitting (#21)	1	4	4	4	4	4

S1: Fossil revival instead of green progress | S2: Technology-open green transformation | S3: Green transformation with hydrogen | S4: Incremental green transformation | S5: Top-down effort & conflicting interests
S6: Bottom-up effort & political inaction
1= highly inconsistent, 2= partly inconsistent, 3= unclear, consistency, 4= consistent, 5= highly consistent

Source: Author's elaboration.