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Abstract

By combining hydrogen and carbon capture and storage (CCS) technologies, the project ELEGANCY aims to accelerate the decarbonisation of Europe's energy system. Within the German case study, different infrastructure options in regard to an integrated H_2-CCS chain – the creation of a CO_2 network for offshore storage in the Netherlands, blending of hydrogen into the natural gas grid and the creation of a dedicated H_2 network – were analysed and assessed. The analysis and assessment include technical, macroeconomic, legal and sociological aspects. The technical analysis describes the modelling of infrastructure options and shows the CO_2 avoidance and costs. In total, with all three options combined in a best case with shipping of CO2 to the Netherlands, hydrogen admixture of 25% and a separate hydrogen network to supply 113 TWh/a over 100 MtCO2/a (12,5% of annual emissions in 2019) can be abated. From a macroeconomic perspective, the infrastructure options are assessed in terms of their economic and political feasibility focusing on (1) complexity, (2) non-economic aspects, (3) uncertainty, and (4) stakeholders. By doing so, factors that foster or hinder a successful implementation of a German infrastructure are identified. In part one, six qualitative socio-technical scenarios were developed that function as an evaluation framework. Part two consists of an interdisciplinary scenario-based infrastructure evaluation. The legal framework for the infrastructure options was analysed with a focus on the provisions for the construction and operation of the respective pipelines, the interaction between infrastructure, law and markets as well as the overall quality of the legal regime. Based on this analysis, the legal research identified the risk and hurdles for the infrastructure options that are connected to the legal framework and discussed possible remedies and their feasibility. From a sociological perspective, social acceptance of the options as well as of H_2 and CCS technologies were examined. In order to analyse acceptance, qualitative interviews with relevant stakeholders and a quantitative survey with people living in Germany were performed. In this way, opportunities and risks for acceptance of the options were identified. The results indicate that there is a high potential for acceptance. However, the acceptance depends on factors which need to be considered in the actual implementation, such as fields of application, energy sources and procedures.

TABLE OF CONTENTS

Page

1 INTRODUCTION

The team of the German case study in the ELEGANCY-project is a interdisciplinary group of researchers at the Ruhr-University Bochum (RUB):

- The technical analysis is performed at the chair for Energy Systems and Energy Economics by Stefan Flamme under the responsibility of Prof. Dr. Valentin Bertsch..
- At the Institute for Macroeconomics, Franziska M. Hoffart performed a scenario-based interdisciplinary analysis under the lead of Prof. Dr. Michael Roos (see section 3).
- At the Insitute for Mining and Energy Law under the lead of Prof. Dr. Johann-Christian Pielow, Dr. Daniel Benrath explores the legal background and potential legislative actions.
- The social acceptance analysis is performed at the chair of sociology, labour and economy by Sabrina Glanz under the lead of Dr. Anna-Lena Schönauer and with the assistance of Ramona Drossner.

The goal of the German case study is to examine a feasible concept for a way to decarbonise the German infrastructure through H_2-CCS chains. The case study is aimed at accelerating the decarbonisation in a bridging period. For this purpose, different infrastructure options are evaluated from an interdisciplinary perspective in terms of their feasibility, especially according to related potentials, costs and risks.

Three infrastructure options for developing the infrastructure are taken into account. These infrastructure options cover a wide range of possible approaches on a conceptual level to integrate the relevant sectors, such as the industry and energy sector, into H_2-CCS chains:

In **infrastrucuture option 1**, carbon dioxide is captured at large point sources and transported to the Netherlands for off-shore storage. This option requires no changes in the existing natural gas infrastructure. Thus, it represents a case, which is comparable to the status quo. It requires, however, the establishment of a new infrastructure to transport CO_2. In **infrastructure option 2**, large amounts of H_2 are produced from natural gas using carbon capture and storage (CCS) in Norway and then, along with green hydrogen from domestic production, is blended in the existing natural gas grid. This option demands broad adjustments of the natural gas grid to adapt to the higher share of H_2. In **infrastructure option 3**, H_2, which is produced in Norway as in option 2, is transported in a dedicated grid to end-users. This option leaves most of the natural gas grid untouched while establishing a new H_2 infrastructure.

1.1 Approach

In the German case study, the three infrastructure options are analysed from different disciplinary perspectives to get a broader assessment. The approach is based on the assumption that the success of infrastructure projects does not only depend on technical aspects but also on economic, legal and sociological issues [FLA19].

Table 1.1: Overview disciplinary contributions.

Discipline	**Focus**	**Methodology**
Technical contribution	CO_2 reduction potential and abatement costs	GIS-based models for the three base options, consisting of future framework conditions and specific data on the H_2/CO_2 sites under consideration are developed. The infrastructure is planned based on the routing of the natural gas network.
Macroeconomic contribution	Conditions that foster or hinder the implementation of a modified gas infrastructure	By using a complexity economic approach, the infrastructure options are assessed in terms of their economic and political feasibility focusing on (1) complexity, (2) non-economic aspects, (3) uncertainty, (4) stakeholders. In part one, six qualitative socio-technical scenarios were developed, that function as an evaluation framework. Part two consists of an interdisciplinary scenario-based infrastructure evaluation.
Legal contribution	Legal costs, risks and constraints; potential legal adjustments	The existing law in regard to major issues is analysed. Additionally, the systematic lines, potentials and constraints for further legal development are examined.
Sociological contribution	Chances and risks for social acceptance of the options and its consequences in the German population	The analysis of social acceptance is based on an empirical study. A mixed-methods-design is applied: Explorative interviews are conducted to capture and understand the stakeholders' perspectives; representative data of social acceptance in the German population is gathered by a quantitative online survey.

Source: based on [BEN19].

These perspectives are combined into a common analysis of the base options and the further exploration of a feasible concept.

1. As the basis of the analysis, the three base options are evaluated from a technical (see section 2), macroeconomic (see section 3), legal (see section 4) and sociological perspective (see section 5). By doing so, the costs, risks and barriers as well as the potentials and benefits related to the infrastructure options are explored and analysed using discipline-specific methods and taking into account the tools created within the ELEGANCY-project.
2. The results of the disciplinary analyses and their interactions are combined into a common analysis and assessment of the infrastructure options. In a first step, the results of the individual disciplines are collected, compared and reciprocally refined. In a second step, discipline-specific results of the individual disciplines are used to assess the three infrastructure options from a joint perspective. For this purpose, the six socio-technical scenarios developed by the macroeconomic researchers function as the evaluation framework (see section 3.3). In addition to a future-robust scenario-based infrastructure assessment (see section 3.3.2), critical key requirements are identified considering the chance of realization and related costs. These critical key requirements are necessary to realise a specific infrastructure option and reveal to be either fostering or hindering (see section 3.3.1).
3. Based on the common analysis of the infrastructure options, the best case options that show to be feasible are determined. These best case options also sport adjustments to the base options to consider the costs, risks and barriers and possible remedies.

4. The best case options are fed into the analyses from the different disciplinary perspectives in a reflective process to gain a deeper understanding of the feasibility, the conditions of success, the risks, the hurdles and the potentials of the best case options.
5. Based on these analyses, feasible concepts to develop the German infrastructure towards a decarbonisation within H_2-CCS chains are presented (see section 6). These concepts are the focal point for recommendations to benefit from the potentials, to mitigate risks and remove hurdles and to address relevant constraints.

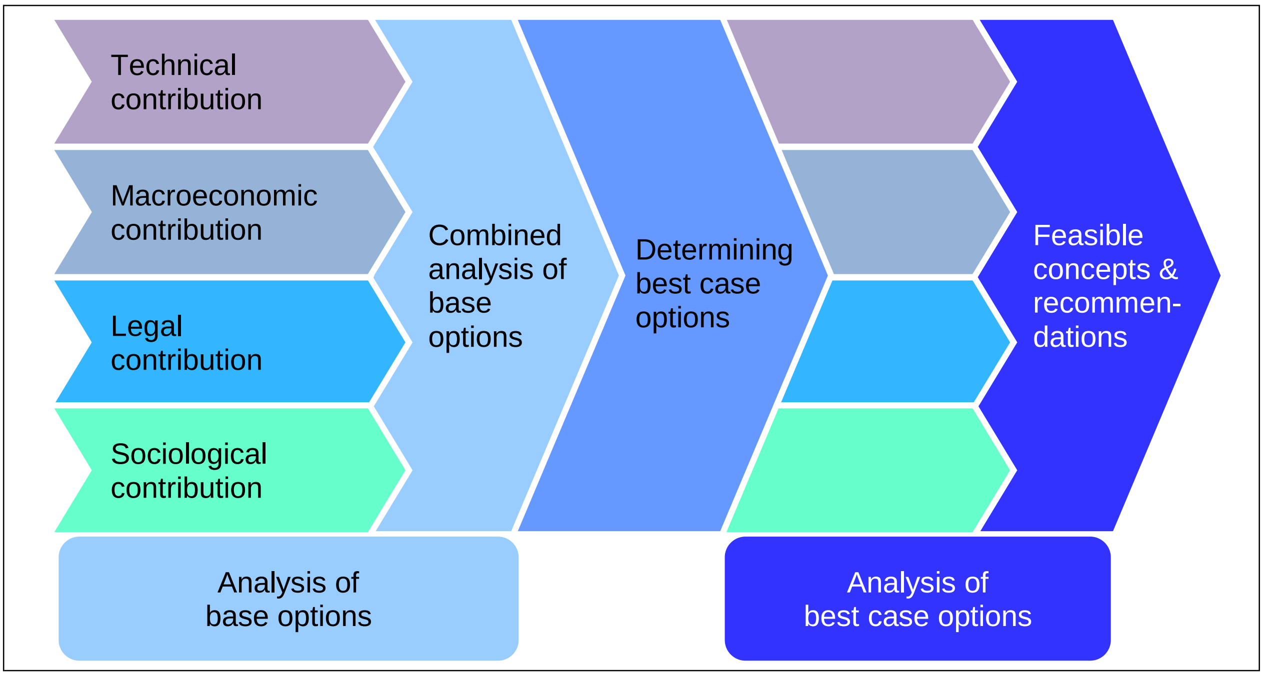

Figure 1.1: Procedure of the final design of the German case study.
Source: based on [BEN19].

1.2 Focus and Scenarios

A common framework in regard to the focus and scenarios align the interdisciplinary perspectives and the further research and analysis.

The examinations are focused on 2035. This open focus describes a bridging period towards an extensive decarbonisation. The timeframe allows taking up the existing economy for extrapolations and gives enough space to plan and implement substantial changes in the infrastructure, without pre-empting the unclear further developments in regard to economy, technology, climate and political conditions. Beyond this focus, the future development towards a significantly reduced role of fossil natural gas as an energy carrier in the gas grids are considered to assess the benefits and drawbacks of the different options.

Other aspects of the common framework concern the different infrastructure options:

- For **option 1**, in respect of carbon dioxide emitters, the current industrial structure without coal power plants is considered. For this option, pipelines and ships are considered as transport options.
- For **option 2**, a general increase of the share of H_2 in the natural gas network is examined. Most of the H_2 is from domestic electrolysis, supplemented by blue hydrogen imported from Norway. Although differences in the regional distribution of H_2 depending on sources can occur and the introduction of separated networks with different shares of H_2 is not to be ruled out, a general increase taking into account regional maximums is an appropriate

conceptual simplification to cover most relevant aspects of this option. For the analysis, technical changes in the existing transmission infrastructure are examined.

- For **option 3**, a basic transport network to connect major suppliers, especially imports from Norway, and major customers of H_2 in the sectors mobility, heating and industry is considered. This approach does not envisage an extensive network, but it is conceptually expandable and thus flexible. A clear focus for option 3 rests on the transmission level, assuming distribution centers in the supplied regions. This simplification is appropriate, as the most relevant challenges for shifting gas supply on the distribution level go well beyond the transport infrastructure anyway [SAD18] while separate analyses of dedicated H_2 distribution networks can easily connect to results in regard to the transmission network. The dedicated H_2 transmission network is based on the routing of existing natural gas pipelines, which also can be adjusted and supplemented.

Taking into account the feedback provided by the Dutch and the Norwegian case study, no limits to the intake capacity for carbon dioxide by the Netherlands or of the supply of H_2 by Norway are considered as relevant.

1.3 References

[BEN19] Benrath, D.; Flamme, S.; Glanz, S.; Hoffart, F.M.: *German Case Study: Final Design and First Results*. *Project Report, Ruhr University Bochum*. – URL: https://www.sintef.no/globalassets/project/elegancy/deliverables/elegancy_d5.5.2_german-case-study_design_first-results.pdf. 2019.

[FLA19] Flamme, S., Benrath, D., Glanz, S., Hoffart, F.M., Pielow, C., Roos, M., Span, R., Wagner, H.-J. and Schönauer, A.-L., ELEGANCY: The interdisciplinary approach of the German case study to enable a low carbon economy by hydrogen and CCS. *Energy Procedia* 158, pp. 3709–3714. – DOI: https://doi.org/10.1016/j.egypro.2019.01.887. 2019.

[SAD18] Sadler, D.; Solgaard Anderson, H.; Sperrink, S. et al.: *H21 North of England. H21 NoE Report/2018*. – URL: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf. 2018.

2 TECHNICAL METHODOLOGY AND RESULTS

The following chapter describes the data basis and the calculations and technical modelling as well as techno-economic results for the three infrastructure options "Carbon Capture and Transport" (1), "Hydrogen Admixture" (2) and "Separate Hydrogen Network" (3).

2.1 General constants and assumptions

For each of the considered infrastructure options, unless otherwise defined there, a number of constants and assumptions for the target year 2035 are used, which are listed in Table 2-1. The base year for all monetary values is $€_{2015}$, the values for investments from other years are scaled using the Kölbel-Schulze Index, an annual factor for the price increases of investments in the chemical industry in Germany.

Table 2-1: General assumptions for the target year 2035.

constant or assumption	**value**	**unit**	**source**
Base year for currency (€)	-	$€_{2015}$	-
electricity price	55	€/MWh	own assumption
natural gas price	28	€/MWh	own assumption
Interest for investments	10	%	own assumption
Lifetime for investments	20	years	own assumption
CO_2 factor electricity grid	267	gCO_2/kWh	own assumption based on climate goals by 2035
Kölbel-Schulze price index for chemical plants	*depending on base year X*	$€_{2015}/€_X$	[VCI17]

2.2 Option 1: Carbon Capture and Transport

Option 1 envisages the capture of CO_2 from large point sources in Germany with transport and storage in the Netherlands. This will be dealt with firstly in relation to capture and subsequently in relation to transport via pipelines and ships.

2.2.1 Carbon Capture

To determine the quantities of CO_2 to be captured, data from the E-PRTR database for the year 2015 was first used, which contains all CO_2 emitters above 100,000 kt/a. Due to the interim developments that led to the decision to phase out coal by the mid-2030s, coal-fired power plants are not considered for the CCT option. In addition to the emitters from the E-PRTR database, pure CO_2 sources from hydrogen production will be considered.

Figure 2.1 shows the cumulative emissions from the groups under consideration: cement and steel industry, refineries, paper production, waste incineration and hydrogen / ammonia production. In total, the sites in these groups emit 145 Mt CO_2/a, which corresponds to almost 20% of annual greenhouse gas emissions in Germany. Steel plants account for the largest share of these emissions with over 30%, followed by refineries and cement plants.

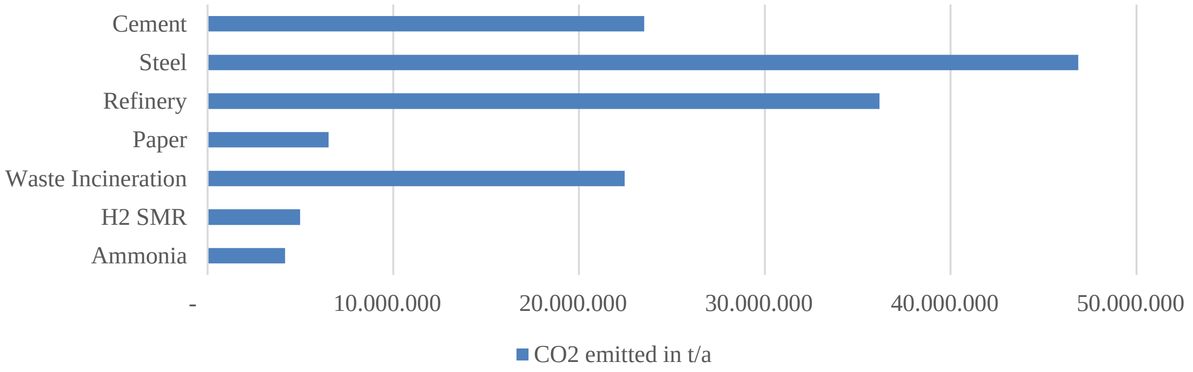

Figure 2.1: Considered CO_2 sources and their annual emissions.

Following in Table 2-2 is a list of the most important assumptions and calculation bases for determining the captured and avoided quantities of CO_2 of the emitter groups. For the calculations, the following assumptions and values were used in addition to those listed in Table 2-1:

Table 2-2: Constants and Assumptions for CCS option.

constant or assumption	value	unit	source
marine diesel oil (MDO) price	298.93	€/t	[ELE18]
natural gas price	28.80	€/MWh	own assumption
CO_2 factor natural gas CHP	205	g/kWh	[ROU16]
CO_2 factor MDO	3.206	$kgCO_2/kgMDO$	[ACO14]
Power eq. factor high temp. steam	0.45	-	[KUR11]
Power eq. factor low pressure steam	0.23	-	[KUR11]
Power eq. factor combined cycle	0.5	-	[KUR11]

The following equation was used to determine the specific quantities of CO_2 avoided [KUR11]:

$$\Delta M_{CO2,sp,avoided} = \frac{M_{CO2,cap} - [\Delta M_{CO2,site} + \{(\Delta P_{Ind} + \Delta H_{Ind} \cdot f_{st,Ind}) + (P_{Cap} + H_{Cap} \cdot f_{st,Cap}) - \Delta F_{gas} \cdot f_{PP}\} \cdot Em_{sp,Elec}}{M_{Ind}}$$

with: $\Delta M_{CO2,Cap}$: CO2 capture rate (tonne/s); $\Delta M_{CO2,site}$: change of total carbon input to the industrial process due to CO2 capture ($t_{CO2\text{-}equivalent/s}$); M_{Ind}: production rate of the industrial product (tonne/s), ΔP_{Ind}: change in the electricity import for the industrial process due to CO2 capture (MW); P_{Cap}: electricity import for CO2 capture and compression (MW); ΔH_{Ind}: change in the steam import for the industrial process due to CO2 capture (MW); H_{Cap}: steam import for CO2 capture and compression (MW); f_{St}: power equivalent factor for steam (dimensionless), ΔF_{gas}: change in the net process gas export from the industrial process to power plants due to CO2 capture (MW), f_{PP}: gas-fired power plant efficiency; $Em_{Sp,Elec}$: CO2 emission factor of grid electricity (t_{CO2}/MJ_e).

For all sites, the final pressure after capture is set at 110 bar; deviations in the literature values are corrected with the following equation [KUR11]:

$$E_{Sp,comp} = \frac{ZRT_1}{M\eta_{is}\eta_m} \cdot \frac{N\gamma}{\gamma - 1}\left\{\left(\frac{p_2}{p_1}\right)^{(\gamma-1)/N\gamma} - 1\right\}$$

with: $E_{Sp,comp}$: specific electricity requirement (kJ/kg CO2); Z: CO2 compressibility factor at 1.013 bar, 15 °C (0.9942); R: universal gas constant (8.3145 J/(mol K)), T_1: suction temperature (313.15 K); γ: specific heat ratio (cp/cv) (1.294), M: molar mass (44.01 g/mol for CO2); η_{is}: isentropic efficiency (80%); η_m: mechanical efficiency (99%), p_1: suction pressure (101 kPa); p_2: discharge pressure (11,000 kPa); N: number of compressor stages (=4)

For the investment costs of the compressor, the following equation from the literature was used, which is then standardised to €$_{2015}$ using the Kölbel-Schulze Index [MAL13]:

$$CAPEXcompressor(€_{2011}) \ = \ 88 \cdot 10\text{^}3 \cdot (P[MW] \cdot 1000)^{0{,}55}$$

The equation takes into account intermediate cooling and drying as well as installation costs (factor 2.5). As operating costs, the value for CO_2 pumping stations, which is 5% of the investment costs, is used [KNO15].

The CO_2 avoidance costs are calculated using the following equation [KUR11]:

$$C_{CO2} = \frac{\alpha \cdot \Delta I + \Delta C_{energy} + \Delta C_{O\&M} + \Delta C_{Mat}}{\Delta M_{CO2,sp,avoided} \cdot M_{Ind,annual}}$$

with: α: annuity factor (1/a); ΔI: additional capital requirement (€); ΔC_{energy}: additional annual cost of energy due to CO2 capture (€/a); $\Delta C_{O\&M}$: incremental annual operation and maintenance (O&M) costs (€/a); ΔC_{Mat}: additional annual cost of raw materials due to CO2 capture (€/a); $M_{CO2,Sp\ avoided}$: specific avoided CO2; $M_{Ind,annual}$: annual production of the industrial product (t/a)

A scaling factor (SF) is used to rescale the investment costs, which takes into account the effects of the different plant sizes according to the following equation:

$$\frac{Cost\ A}{Cost\ B} = (\frac{Scale\ A}{Scale\ B})^{SF}$$

2.2.1.1 Ammonia Industry

An average of 2.5 million tons of ammonia are produced per year, whereby 178 kg of hydrogen are required per ton of ammonia. [NRW19] This hydrogen is currently still produced by steam reforming of methane, with 9 kg CO_2 per kg H_2 being released into the atmosphere [GRE19]. For the total amount of CO_2 emitted per ton of ammonia, the average value of 1.569 kg CO_2 per kg ammonia from [GFC19], [DBT18] and the above-mentioned value for SMR is used. Of this amount, 1.2 kg of CO_2 per kg of ammonia is present as pure CO_2 stream, which corresponds to a total CO_2 quantity of 3 Mt/a [FAR95]. However, since part of the pure CO_2 is used for the production of 290 Mt/a urea (0.76 tCO_2/tUrea), 220 kt/a (7%) of the pure CO_2 is subtracted [DES18], [WIK20]. Furthermore, about 14% of the pure CO_2 is used in the food industry [FAR95]. This leads to a share of about 78% of the pure CO_2 or 60% of the total emissions of the ammonia industry, which is available for CCS.

For the H_2 production sites of the ammonia industry and their capacities, a deliverable of the project "Roads2HyCom" was used, which lists all H_2 production sites by subgroups, locations, utilisation and daily capacities [ROA07].

Table 2-3 shows values for CO_2 capture at an ammonia site with a production capacity of 0.25 Mt/a. It should be noted that the values given for CAPEX and avoidance costs depend on the plant size and change non-linearly by the scale factor given. For separation at ammonia sites only a compression to 110 bar with drying and intercooling of the pure CO_2 stream is assumed (compressor data: see previous section 2.2.1). The scale factor for the investment is already included in the above-mentioned formula for the compressor.

Table 2-3: Values for CO_2 capture at an ammonia site with a production capacity of 0.25 Mt/a, based on the pure CO_2 stream.

CO_2 per ton of product	**available for capture**	**cap. eff.**	**electricity demand**	**steam demand**	**CO_2 avoided**	**scaling factor (SF)**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[tCO_2/ tProd.]	**[tCO_2/ tProd.]**	**%**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**%**		**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
1.569	0.936	100%	0.4	-	97%	-	7.51	5%	1.46	11.71

[1]: for an exemplary site with a production of 0.25 Mt Ammonia/a

2.2.1.2 Hydrogen SMR & Refinery Hydrogen Production

For the H_2 production sites and their capacities, the deliverable of the project "Roads2HyCom" was also used, which contains a list of all H_2 production sites by subgroup, location, use and daily capacities [ROA07]. In this category all sites of the type "Refinery SMR" and "H_2 SMR" are considered.

According to [DNV10], the steam reforming of natural gas to hydrogen produces a pure CO_2 stream containing about 60% of the total emissions. This value is set off against the total of 9 kg CO_2 per kg H_2, which results in a pure CO_2 stream of 6 kg CO_2 per kg H_2. The CO_2 stream is then only compressed and dehumidified, as is the case in the ammonia industry. The scale factor for the investment is already included in the previously mentioned formula for the compressor. Table 2-4 contains the values for an example SMR plant with a capacity of 78 kt H_2/a.

Table 2-4: Values for CO_2 capture at an H_2-SMR site with a production capacity of 78 kt/a, based on the pure CO_2 stream

CO_2 per ton of product	**available for capture**	**cap. eff.**	**electricity demand**	**steam demand**	**CO_2 avoided**	**scaling factor (SF)**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[tCO_2/ tProd.]	**[tCO_2/ tProd.]**	**%**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**%**	**-**	**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
9	6	100%	0.4	-	97%	-	10.2	5%	2.54	10.51

[1]: for an exemplary site with a production of 78 kt H_2/a

2.2.1.3 Refinery stacks

For the refinery stacks the values from the E-PRTR database are used. Assuming that 65% of the refinery's emissions come from boilers and furnaces whose exhaust gases are emitted in central stacks, 65% of the total emissions from the refinery sites are thus part of the further considerations [KUR11]. Values from [KUR11] are used for the design of the capture process and adjusted to "Steam Import" instead of "NG-CHP". Post-combustion capture with MEA is used as the capture method. Table 2-5 shows the calculation bases for an exemplary refinery site with 3 Mt CO_2/a total emissions.

Table 2-5: Values for CO_2 capture at a refinery site with 3 Mt CO_2/a total emissions..

CO_2 emitted	**available for capture**	**cap. eff.**	**electricity demand**	**steam demand**	**CO_2 avoided**	**scaling factor (SF)**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[Mt CO_2/a]	**[tCO_2/ tCO_2]**	**%**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**%**	**-**	**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
3	65%	90%	0.55	4.21	53%	0.67	315.3	12%	67.8	88.05

[1]: for an exemplary site with emissions of 3 Mt CO_2/a

2.2.1.4 Cement production

For the CO_2 sources of cement production, the data of the E-PRTR database is also used. The value 0.8 tCO_2 per t clinker is used to determine the annual clinker production quantity from the CO_2 emissions [VDZ08]. Post combustion capture with MEA and steam import is used for the design of the CO_2 capture [KUR11].

Table 2-6: Values for CO_2 capture at a cement site with a production capacity of 1 Mt clinker/a.

CO_2 per ton of product	**available for capture**	**cap. eff.**	**electricity demand**	**steam demand**	**CO_2 avoided**	**scaling factor (SF)**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[tCO_2/ tProd.]	**[tCO_2/ tCO_2]**	**%**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**%**	**-**	**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
0.8	100%	85%	0.55	4.21	53%	0.67	315.3	12%	67.8	88.05

[1]: for an exemplary site with emissions of 3 Mt CO_2/a

2.2.1.5 Steel production

For the steel industry's CO_2 sources, the data contained in the E-PRTR database is not used, as it is subject to excessive fluctuations due to gas exports and localization problems. Instead, based on the annual production volume from 2015, the CO_2 emissions of the sites are calculated with a factor of 1.7 tCO_2 per t hot rolled coil (HRC) [KUR11], [WVS16]. The separation always takes place at the blast furnace and was calculated in advance with four variants (MEA, KS-1, TGR[1]+MEA und TGR+VPSA[2]) [KUR11]. It was found that the Top Gas Recycling plus VPSA case is the most cost-effective. Further assumptions relevant for the calculation were also made. With the TGR process, less blast furnace gas (blast furnace gas) can be sold or energetically used (-2600 MJ/t pig iron), and 350 MJ/t pig iron less is generated by the blast furnace air turbine. By recirculating the blast furnace gas, 0.1 t of coke per t of pig iron is saved. [BAT13], [KUR11], [WEI14] All in all, more CO_2 can be avoided than captured due to the above mentioned assumptions and change of energy and material flows (see Table 2-7).

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[1] Top Gas Recycling: Process in which the BF gas contains much more CO_2 than CO compared to the standard blast furnace process

[2] Vacuum Pressure Swing Adsorption

Table 2-7: Values for CO_2 capture at a steel plant with VPSA+TGR and a production capacity of 4 Mt hot rolled coil/a.

CO_2 per ton of product	**available for capture**	**CO2 captured**	**electricity demand**	**steam demand**	**CO_2 avoided**	**SF**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[tCO_2/ tProd.]	**[tCO_2/ tProd.]**	**[tCO_2/ tProd.]**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**[tCO_2/ tProd.]**	**-**	**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
1.7	~0.9	0.83	0.94	-	0.86	0.67	150.1	6%	118.2	41.97

[1]: for an exemplary site with emissions of 4 Mt HRC/a

2.2.1.6 Paper production

For the emissions of the paper mills' sites, data from the E-PRTR database is used. Post combustion capture with MEA is used as separation technique, whereby three different types of steam generation are available, by means of heat pump, natural gas CHP or steam import [HEK09]. Here the case of the heat pump was chosen because it can be operated independently from the location and, depending on the electricity used, also without the use of fossil fuels. The capture takes place at the recovery boiler, which accounts for 68% of the total emissions of the paper mill [KUP19]. The data for the case described can be found in Table 2-8.

Table 2-8: Values for CO_2 capture at a paper site with MEA+ heat pump and a total CO_2 emission of 0.258 Mt CO_2/a.

CO_2 emit.	**available for capture**	**cap. eff.**	**electricity demand**	**steam demand**	**CO_2 avoided**	**scaling factor (SF)**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[Mt CO_2/a]	**[tCO2/ tCO_2]**	**%**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**%**	**-**	**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
0.258	68%	90%	1.11	-	57%	0.7	25.4	4%	2.7	45.44

[1]: for an exemplary site with annual CO_2 emissions of 0.258 Mt CO_2/a

2.2.1.7 Waste incineration

The data on waste incineration plant sites and their CO_2 emissions were taken from the E-PRTR database. Post combustion capture with MEA is used for CO_2 capture, the steam required for regeneration is taken from the turbine [YOU18]. Since the investment costs from [YOU18] seem very low, a value for the capture equipment and compressor in paper mills with a scale factor of 0.7 is used instead [HEK09].

Table 2-9: Values for CO_2 capture at a waste incineration plant site with MEA+steam extraction and total CO_2 emissions of 0.391 Mt CO_2/a..

CO_2 emitted	**available for capture**	**cap. eff.**	**electricity demand**	**steam demand**	**CO_2 avoided**	**scaling factor (SF)**	**CAPEX**	**OPEX**	**Energy costs**	**Abatement costs**
[Mt CO_2/a]	**[tCO_2/ tCO_2]**	**%**	**[GJ/ tCO_2]**	**[GJ/ tCO_2]**	**%**	**-**	**[M€][1]**	**% of CAPEX**	**[M€/a][1]**	**[€/tCO_2][1]**
0.391	100%	95%	0.48	4	86%	0.7	41.9	4%	7.3	41.34

[1]: for an exemplary site with annual CO_2 emissions of 0.391 Mt CO_2/a

2.2.1.8 Overview of all sites considered

Figure 2.2 shows the proportion of total emissions from the sites under consideration that can be avoided by the capture processes described above. The emissions caused by the capture process itself have already been set off against the value for avoided CO_2.

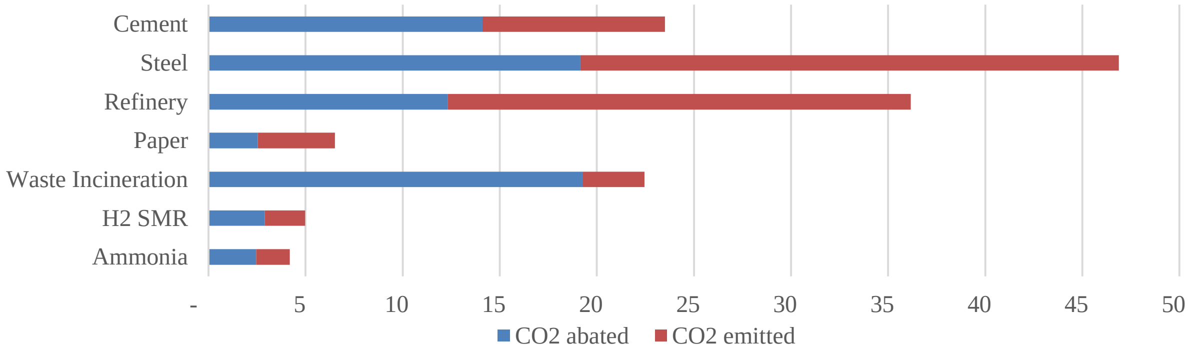

Figure 2.2: Abatement potential in relation to total emissions.

Figure 2.3 gives an overview of the spread of costs within the groups considered and between the groups. It shows that hydrogen-related sites, especially those from the ammonia industry and SMRs at refineries, have relatively low CO_2 abatement costs of less than 20 €/tCO_2. The large number of very small plants results in a cost range for H_2 SMR from 10 to over 60 €/tCO_2 due to economy of scale effects of the compressor. In the middle range between 40 and 50 €/tCO_2 are almost all sites from the waste incineration, paper and steel production sectors. The cement plants have a range of slightly over 60 €/tCO_2 to 90 €/tCO_2. Refinery stack capture is the most expensive by comparison, ranging from 87 to 120 €/tCO_2.

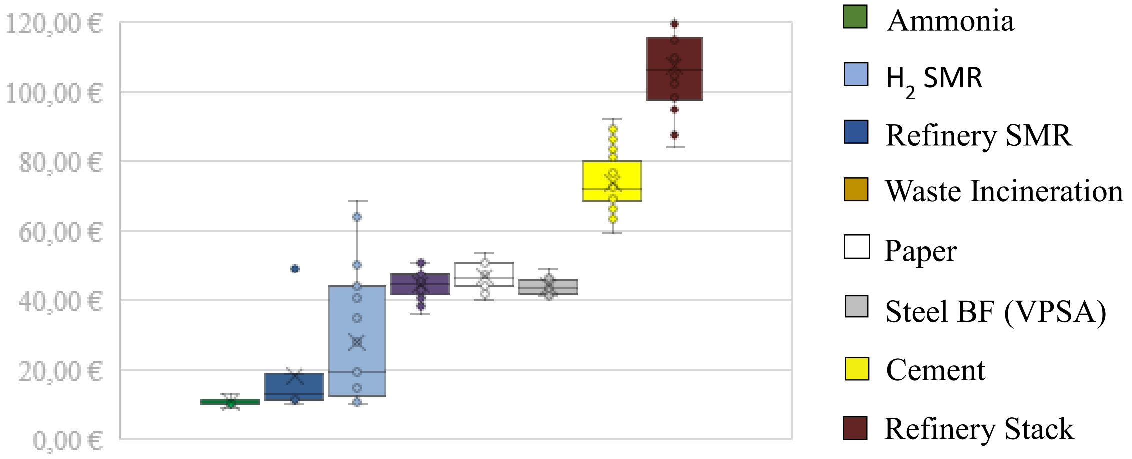

Figure 2.3: Avoidance cost range of all CO2 sites.

In order to limit the negative effects of economies of scale, a lower limit of 250 ktCO_2/a is set for further considerations, and an upper limit of 70 €/tCO_2 for abatement costs (see Figure 2.4). Within these limits, 70% of the abatement potential (50.74 MtCO_2/a captured, 48.8 MtCO_2/a avoided) of all CO_2 sources under consideration remain.

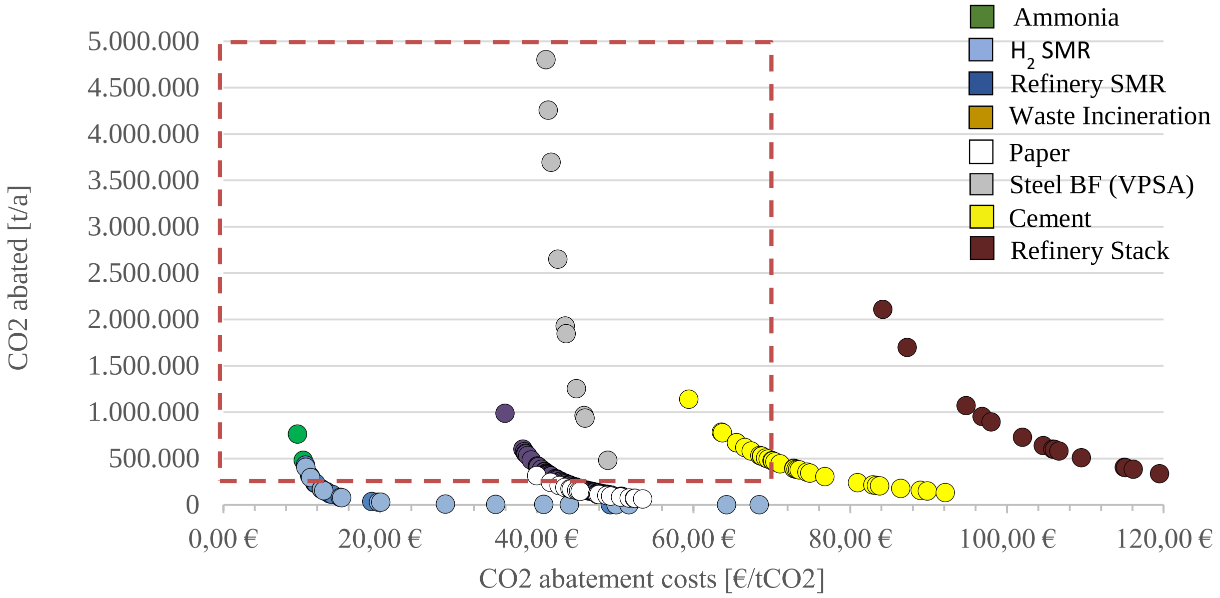

Figure 2.4: Selection of CO_2 sources >250 kt/a and <70 €/tCO_2.

2.2.2 CO2 Transport

First of all, the CO_2 sources selected in the previous section are presented with regard to their location relative to the federal waterways and the natural gas pipeline network (see Figure 2.5). It can be seen that most of the sources are located near both the federal waterways and the natural gas grid, which is why both transport options, pipeline and ship transport, are examined below.

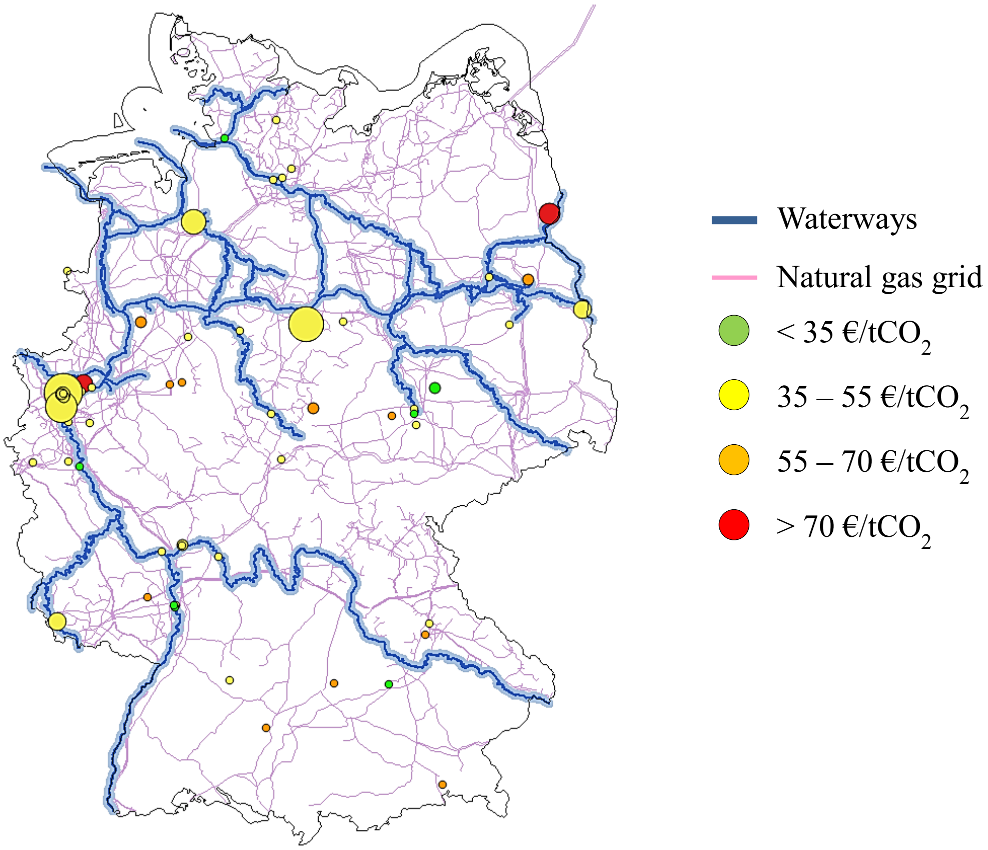

Figure 2.5: CO_2 sources scaled by avoided CO_2 and categorized by avoidance costs.

2.2.2.1 Pipeline transport

For pipeline transport, the substance data of the transported mixture are first listed in Table 2-11. The inlet pressure into the pipeline system is 110 bar (cf. section 2.2.1), the inlet temperature is 30°C and the average temperature in the pipeline system is assumed to be 22°C. For the composition, impurities from steel and cement plants, refinery stacks and combustion plants are assumed to be the worst-case scenario in order to ensure transport as a dense fluid (cf. Table 2-10).

Table 2-10: Worst-case composition of CO_2 stream [CLU19].

CO_2	N_2	O_2	Ar	H_2O	NO_x	SO_2	SO_3	CO
99.930%	0.023%	0.015%	0.023%	0.005%	0.003%	0.000%	0.000%	0.001%

For this composition the density of the mixture at 22°C was calculated with the TREND[3] tool (see Figure 2.6). Since the CO_2 mixture enters the pipeline at 30°C and is repeatedly recompressed, and since the CO_2 density remains relatively constant with a simultaneous drop in pressure and temperature at this state, a density of 790 kg/m³ is used for the further calculations.

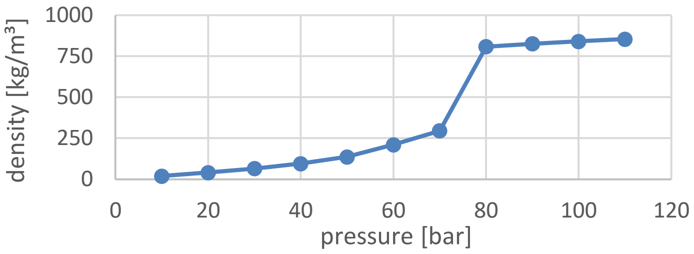

Figure 2.6: Density over pressure for 22°C and worst-case mixture.

The assumptions and substance properties used can be found in Table 2-11.

Table 2-11: Constants for CO_2 pipeline transport

Pipeline inlet pressure	Pipeline min. pressure	Pipeline inlet temperature	Pipeline average temperature	density (ρ)	dyn. viscosity (η)	Roughness of pipeline (ε)
[bar]	[bar]	[°C]	[°C]	[kg/m³]	[x10^{-6} Pa·s]	[m]
110	86	30	22	790	71.5877	0.0000417

The following general equations and calculations of the pipelines are also used for the modelling of the H_2-pipelines (see 2.4.2).
The following equation is used to determine the pipe inner diameter (D) [IEA05]:

$$D = \left(\frac{F}{v \cdot \pi \cdot 0.25 \cdot \rho}\right)^{0.5}$$

with: D: inner diameter [m]; F: flow rate [kg/s]; v: transport velocity [m/s]; ρ: density [kg/s]

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[3] Thermodynamic Reference and Engineering Data, Chair for Thermodynamics at RUB

All input variables except for the transport velocity are predefined, which makes the latter a decisive design factor, since with increasing transport velocity the diameter decreases, but the pressure losses in the pipe section increase - resulting in more frequent recompression.

To determine the pressure losses, the Haaland approximation of the Darcy Friction Factor (f) is used, which provides a good average value among the common approximations [PEL18].

$$\frac{1}{\sqrt{f}} = -1.8 \cdot \log_{10}[\left(\frac{\frac{\varepsilon}{D}}{3.7}\right)^{1.11} + \frac{6.9}{Re}]$$

with: f: friction factor [-]; ε: pipe roughness [m]; D: inner diameter [m]; Re: Reynolds number $Re = \frac{\rho \cdot v \cdot D}{\eta}$ [-]; v: transport velocity [m/s]; ρ: density [kg/s]; η: dyn. viscosity [Pa·s]

With this, the pressure losses Δp are calculated using the Darcy-Weisbach equation [JRC11]:

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2}$$

with: Δp: pressure losses [Pa]; f: Darcy friction factor [-]; D: inner diameter [m]; L: pipe length [m]; v: transport velocity [m/s]; ρ: density [kg/s];

If the equation is divided by the length L, the specific pressure drop $\frac{\Delta p}{L}$ per metre can be calculated. From this, the maximum transport distance L_{crit} within the desired pressure range can be determined by dividing the maximum pressure loss, here (110 - 86 = 24 bar) by the specific pressure loss per metre. The number of pumping stations $N_{booster}$ is calculated by rounding up the ratio of L to Lcrit, using a booster station above pressure losses of 1.5 bar per section.

The next section contains the assumptions and cost functions specifically used for pipeline transport of CO_2.

First, a cost function of the IEA is used for the pipeline costs [IEA05]:

$$I_{pipeline,IEA} = (C_1 \cdot L + C_2 + (C_3 \cdot L - C_4) \cdot D + (C_5 \cdot L - C_6) \cdot D^2) \cdot 10^6 \cdot TF$$

with: $I_{pipeline,IEA}$: investment costs pipeline [$€_{2000}$]; L: pipeline length; D: pipeline diameter [inch]; TF: terrain factor average = 1,2 [-] and factors for onshore pipelines: $C_1 = 0.057$; $C_2 = 1.8663$; $C_3 = 0.00129$; $C_4 = 0.0113$; $C_5 = 0.000486$; $C_6 = 0.000204$

To better represent the range of investment costs, a second cost function by Parker et al. is used, which, in addition to material costs, explicitly includes labour, ROW and other costs [KNO15]:

$$I_{pipeline,Parker} = (996820 \cdot D^2 + 441912 \cdot D + 223522) \cdot L + 545537$$

with: $I_{pipeline,Parker}$: investment costs pipeline [$€_{2010}$]; D: inner diameter pipeline [m]; L: pipeline length [m]

For each section, the investment costs are adjusted to $€_{2015}$ and the average value of the results of the two equations is used.

Since the value for the investment costs of pumping stations varies considerably in the literature used, an average value from two cost functions is also used for this purpose. The first cost function assumes constant costs per km, independent of the mass flow [IEA05]:

$$I_{BS,IEA} = L \cdot 35000 \frac{€}{km}$$

with $I_{BS,IEA}$: investment costs booster station [$€_{2000}$]; L: pipeline length [km]

The second equation for the investment costs of pumping stations by Chandel et al. depends on the pumping capacity [KNO15]:

$$I_{BS,Chandel} = (P_{Pump} \cdot 2.3 + 0.15) \cdot 10^6$$

with: $I_{BS,Chandel}$: investment costs booster station [$€_{2010}$]; P_{Pump}: capacity [MW_{el}]

The pumping capacity P_{Pump} is calculated with the following equation [IEA05]:

$$P_{Pump} = \frac{\frac{1}{\rho} \cdot \frac{\Delta p}{\eta_{Pump}}}{L_{BS}}$$

with: P_{Pump}: pumping station capacity [MW]; ρ: density [kg/s]; Δp= pressure losses [Pa]; η_{Pump}: 75%; L_{BS}: length of pipeline segment until booster station is needed (for $\Delta p \geq 24$ bar: $L_{BS} = L_{crit}$; for $\Delta p < 24$ bar: $L_{BS} = L$)

The annual operating costs (excluding energy costs) for pipelines are estimated at 3% (IEA) or 2.5% (Parker) of the total investment costs. For pumping stations, a value of 5% of I_{BS} is used for both cases. [IEA05], [KNO15] The equation for CO_2 compression from section 2.2.1 is used to calculate the pumping capacity.

To determine the costs per transported tonne of CO_2, the investments are annualised (20a, 10%).

Figure 2.7 shows the pipeline route that transports the captured CO_2 emissions of the remaining sites (orange) along the routing of the natural gas network (blue) with a CO_2 pipeline system (pink) to the Netherlands. Likewise, the various mix points, between which the route sections considered are located and whose design and optimisation is described below, are represented by round markings on the pipelines. Each section extends from one entry point to the next, which is why the mass flow transported in one section is constant.

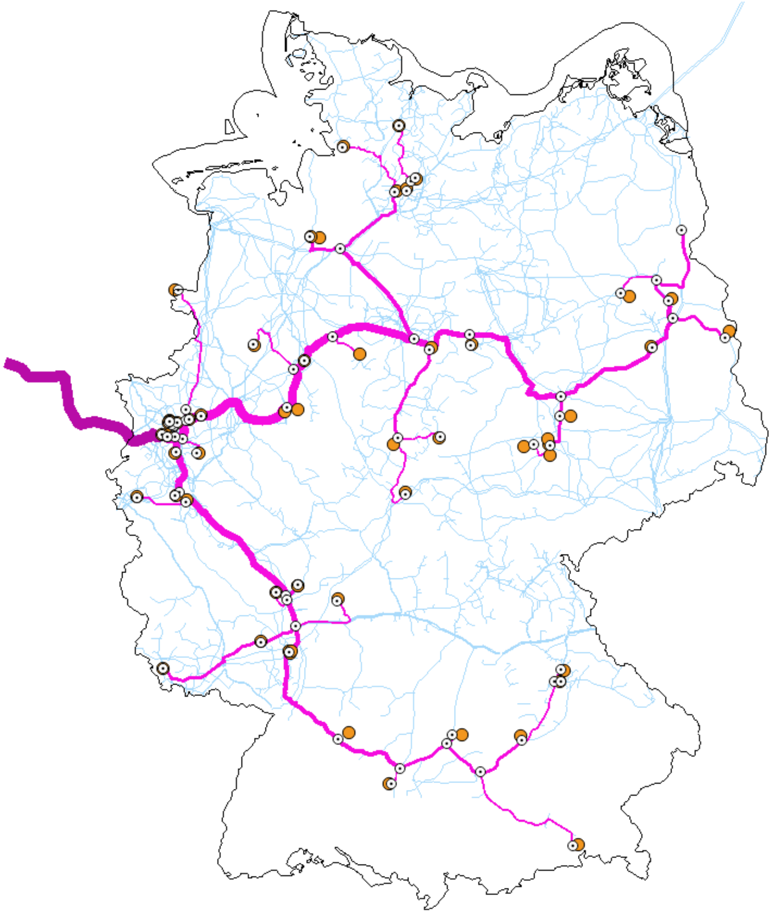

Figure 2.7: CO_2 sources, network and mix points in relation to natural gas grid.

Now, for each of the 76 route sections, whose total length amounts to just under 3193 km within Germany, a cost minimisation is carried out by varying the transport velocity, which influences the pipeline diameter, using a solver. The higher the flow velocity, the smaller the pipe diameter - but this also increases the pressure losses, making more pumping stations necessary in the particular section. As boundary conditions for the solver, the maximum number of pumping stations is limited to 3 per section, the transport velocity can vary between 1 and 4 m/s. It appears that in almost all sections it is more favourable to use at least one pumping station instead of using a larger pipe diameter. Table 2-12 shows on the left the number of sections with 0, 1, 2 or 3 pumping stations, in the centre the minimum, maximum and average transport costs and on the right the minimum, maximum and average diameter of each section. In addition to the routes in Germany, a 208 km long collection pipeline was laid to Rotterdam assuming the CO_2 being transported from there to the offshore storage facilities.

Table 2-12: Statistical data on the CO_2 pipeline sections within Germany.

number of booster stations	count
0	5
1	43
2	12
3	15

transport costs of segments [€/tCO_2]	
Min	0.03
Max	23.47
Average	2.97

inner diameter of pipeline segments [m]	
Min	0.10
Max	0.95
Average	0.32

The total transport costs allocated per tonne of CO_2 within the German borders amount to 5.96 €/tCO_2. The pipeline to the Netherlands costs additional 1.38 €/tCO_2, resulting in total transport costs of 7.34 €/tCO_2. Figure 2.8 shows the pipeline sections in Germany, coloured by the transport costs per tonne of CO_2. The red sections are more cost-intensive relative to the amount of CO_2 transported than the green sections and if necessary, could be removed from the pipeline planning to reduce costs.

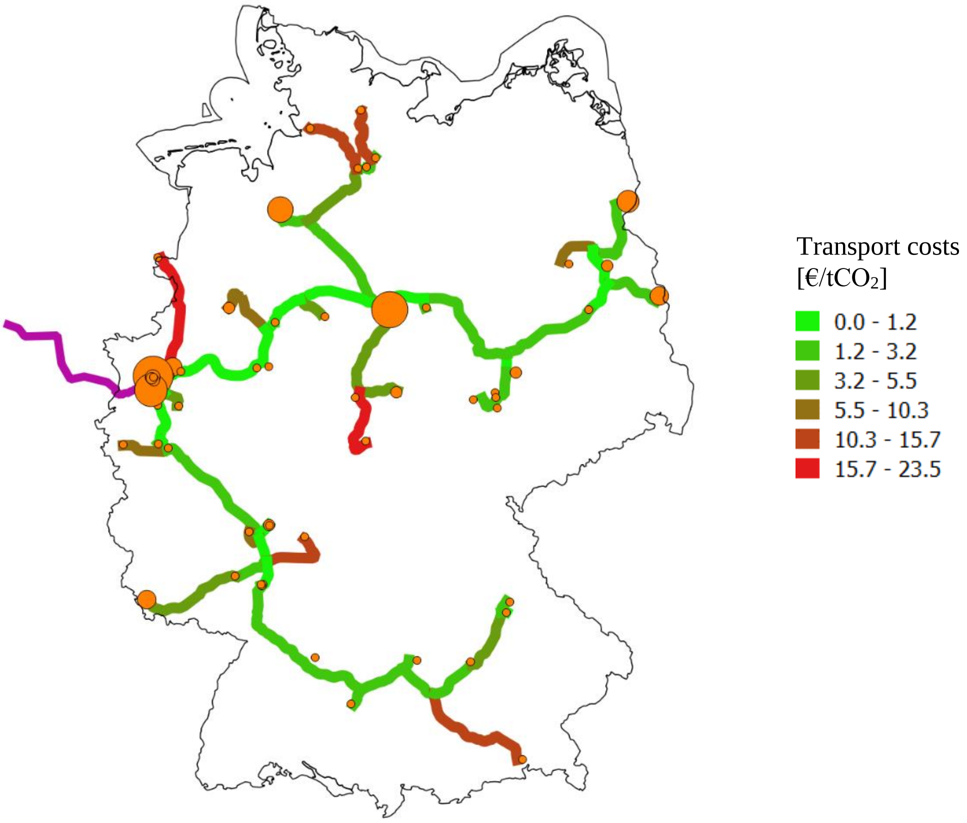

Figure 2.8: CO_2 pipeline sections coloured by transport costs.

Figure 2.9 shows the annual costs of the pipeline system, with the investment costs being apportioned on an annuity basis as mentioned before. It can be seen that the pipelines themselves account for the largest share, the pumping stations represent the smallest share.

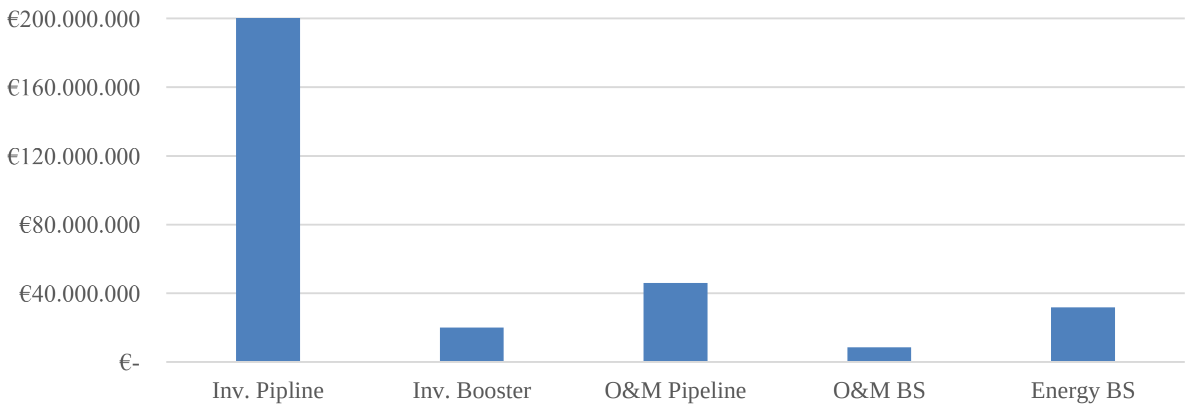

Figure 2.9: Annual costs of CO_2 pipeline system.

The electricity used for the pumping stations causes annual emissions of 0.15 $MtCO_2/a$ (at 267 gCO_2/kWh), which are deducted from the avoided emissions. This results in a total of 48.65 $MtCO_2/a$ that can be avoided.

2.2.2.2 *Ship transport*

Initially, five transport routes will be identified for ship transport via federal waterways, with the aim of having as many CO_2 sources as possible on one route. Locations that are too far away from the waterways will not be considered further. This results in a total of 43.23 $MtCO_2$ that can be transported for storage in an offshore gas field in the Netherlands. At sites located directly on the water, only the loading infrastructure will be installed. At sites that are close to but not directly at the river, small local pipeline systems bring the CO_2 to the loading station at the waterway. Figure 2.10 shows the five water transport routes A-E (blue), the remaining CO_2 sources (green), the loading stations (black symbols) and CO_2 pipelines (pink).

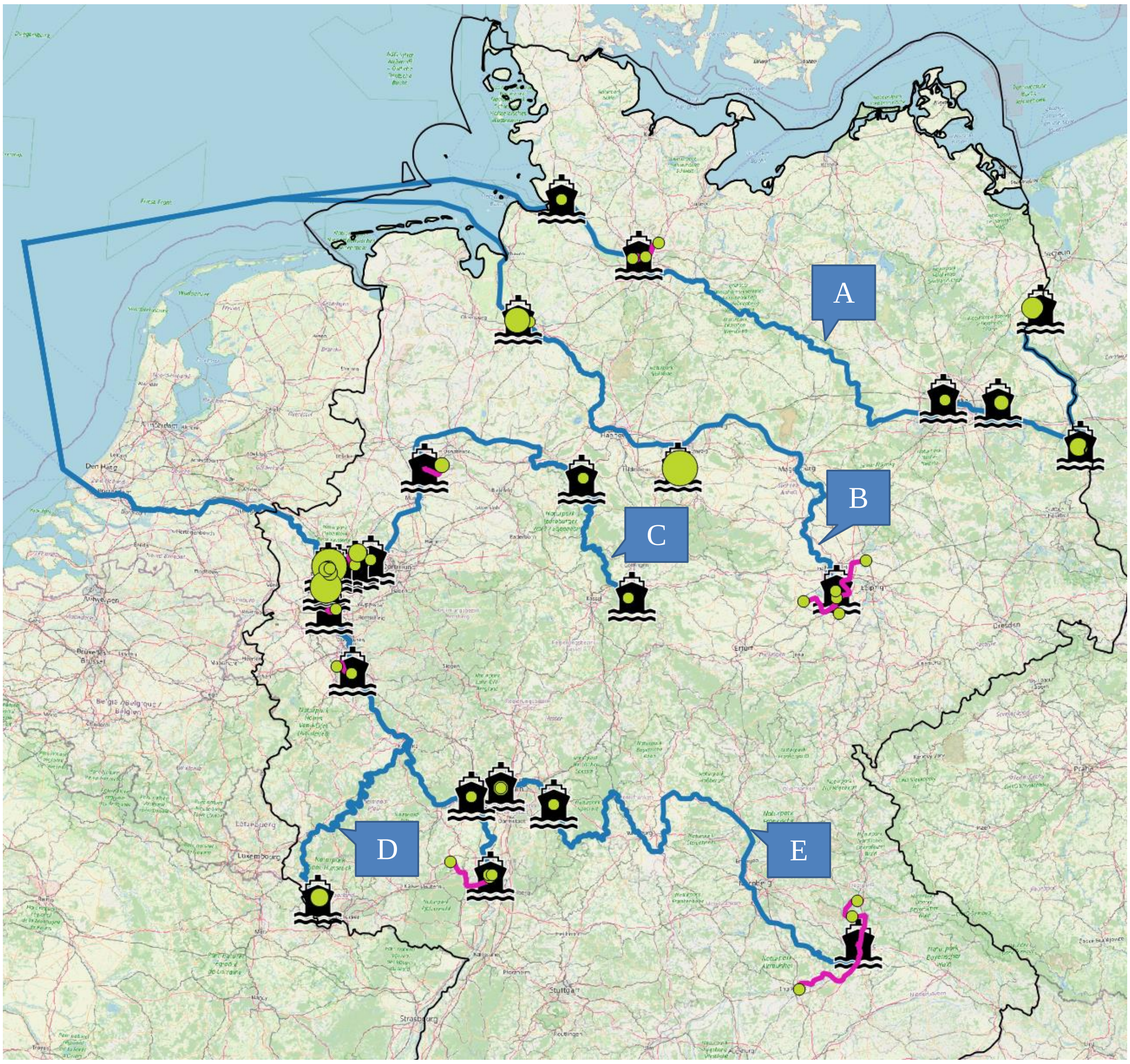

Figure 2.10: Water transport routes (blue), remaining CO_2 sources (green), loading stations (black symbols) and CO_2 pipelines (pink). Map in background © OpenStreetMap contributors

The next step is to determine the number and size of the required ships. It is assumed that a ship will load per trip along its assigned transport route the share of one trip in the total annual quantity of each site, calculated by dividing the total annual quantity of CO_2 at the site by the annual trips made by the ships on the route. For the quantities transported per section of the route between two loading points, the quantity transported per year is calculated, with the quantities "upstream" adding up, as the ships start loading at the end of the transport route. This value can then again be offset against the number of ships required.

Two main sources are referred to for the further calculations ([KNO15], [ELE18]), but these sources themselves use a variety of other sources for the calculations of the individual components of the transport chain.

Due to the large quantities of CO_2, only a big ship capacity of 50 ktCO_2 is used [KNO15]. The investment costs are calculated with an equation from [ELE18], which is based on literature values. The fuel consumption of the ships originates from [KNO15], where it was taken from Roussanaly et al.[4] and is actually valid for 45 kt ships, so for 50 kt it is rather conservative, since the specific consumption decreases with the loading capacity. The price for MDO (Marine Diesel Oil) is 298.93 €$_{2015}$/t [ELE18]. The speed is assumed to be 16.5 knots, the loading time is 12h [KNO15], the unloading time 36h [ELE18]. The availability of a ship is assumed to be 350 days per year. [KNO15].

Table 2-13: Assumptions and calculations for the required ships.

shipp-ing routes	route length (one way)	CO_2 transpor-ted	trips per a	number of ships	ship scale [kt]	Inv. costs	spec. fuel consump-tion	annual fuel consump-tion	fuel costs	time for 1 trip and back	max trips per ship & year	port fees
-	[km]	[Mt/a]	[-]	[-]	50	[M€/ ship]	[g fuel/ tCO_2/km]	[kt/a]	[M€/a]	h/a	[-]	[M€ /a]
A	1100.7	7.43	149	4.00	50	71.78	5.4	34.7	10.4	192.67	43	3.5
B	959.0	9.77	196	4.00	50	71.78	5.4	35.5	10.6	145.77	57	4.5
C	903.3	13.55	271	7.00	50	71.78	5.4	33.5	10.0	189.48	44	6.3
D	879.3	6.72	135	3.00	50	71.78	5.4	20.7	6.2	151.64	55	3.1
E	1435.6	5.76	116	3.00	50	71.78	5.4	31.3	9.4	206.43	40	2.7
ALL	**5277.9**	**43.23**	**867**	**21**	-	-	-	**201.8**	**46.5**	-	-	**20.1**

Assuming a lifetime of 25 years and an interest rate of 10% results in annual investment costs of 166 million €, fuel costs of 46.5 million € and operating costs of 75.4 million € (5% of investment). In terms of CO_2 transported per tonne of CO_2, this represents a cost of 7.12 €/tCO_2.

The next step is to determine the cost of loading and the infrastructure required for this. Basically, the loading concept looks like this:

CO_2 site → (pipeline) → liquefaction → temporary storage → loading

---

[4] The value corresponds to a laden outward trip and an empty return trip, was communicated by Simon Roussanaly (SINTEF) on request.

For pipeline transport, which becomes necessary if the site is not located directly on the waterway, the calculation is based on the methods described in 2.2.2. This results in costs of 0.54 €/tCO_2 for the 450 km of pipelines indicated in Figure 2.10.

The installations for loading the ships are also assumed to have a lifetime of 25 years and an interest rate of 10%.

For the liquefaction plants, a basic size is used with a scaling factor. The basic costs for a liquefaction plant with a capacity of 20 Mt/a are 147 M€$_{2010}$, the scaling factor is 0.9. The energy consumption of the liquefaction plants is 39 kWh/tCO_2 (at 55€/MWh), the water consumption is 3.38 m^3/tCO_2, the costs are 0.14 €/m^3. The other operating costs are assumed to be 5% of the total investment. [KNO15] For the 25 loading terminals, this results in a total specific liquefaction cost of 4.19 €/tCO_2.

A floating vessel, i.e. a ship anchored at the site, is used as a temporary storage. This is to represent the most cost-effective variant of a temporary storage facility. The size of the vessel is calculated from the statistical load of a ship per trip at the respective location, scaled up by a factor of 1.2. The basic cost is 1 million € per 1000 m^3, the scaling factor is 1, the operating costs 5% of the total investment. [KNO15] For all 25 sites, the specific costs of the temporary storage facility are 0.95 € per tCO_2.

Specific investment costs of 1.52 million €$_{2015}$ per tonne of CO_2 are used for the loading equipment, with operating costs amounting to 3% of the total investment. In total, the specific costs for the loading equipment of all 25 sites amount to 0.21 €/tCO_2. [ELE18]

As a subtotal excluding unloading at the storage site, the sum of the costs of ships and loading infrastructure gives a specific cost of 13.01 €/tCO_2.

At the storage site (offshore), a further intermediate storage vessel is required, the size of which is assumed here to be 1.2 times the capacity of the vessels used. This ship is assumed to be 15% of the cost of the actively used ships, since an old ship is sufficient as storage. The additional retrofitting costs for a storage capacity of 40000 m^3 amount to 25 million €$_{2010}$ with a scale factor of 0.69. [KNO15]. The total cost of offshore storage is 0.17 €/tCO_2.

The offloading system is assumed to have a base cost of 30 million €$_{2010}$ for a discharge capacity of 1200 tCO_2/h with a scale factor of 0.29, the operating costs are 5% of the total investment [KNO15]. The total specific unloading cost is 0.18 €/tCO_2.

For the conditioning of CO_2 for storage, a base cost of 2 million €2010 for a capacity of 350 tCO_2/h with a scaling factor of 0.56 and operating costs of 5% is used. The energy input covered by a marine diesel-powered generator is 0.66 tonnes of diesel per tonne of CO_2. [KNO15] The total specific cost of this is 0.21 €/tCO_2.

The specific total costs for loading, transport and unloading are 13.57 €/tCO_2.

2.3 Option 2: Hydrogen Admixture

Option 2 examines the blending of larger quantities of hydrogen into the natural gas network, starting by examining the compatibility of the infrastructure and the additional costs of the necessary adjustments. The results are largely based on studies carried out by the German Technical and Scientific Association for Gas and Water (DVGW), as through its members it has access to the necessary resources and concrete data of gas network operators, which are otherwise not freely available. Therefore, the discussion of this option in the present deliverable is somewhat shorter than that of the other two options.

2.3.1 Hydrogen Compatibility

2.3.1.1 Current Regulations

According to DIN EN 51624, 2% hydrogen is tolerated in the natural gas grid. Due to the danger of hydrogen embrittlement of natural gas tanks in passenger cars, the mixing ratio cannot be increased. In the DVGW rules and regulations "Arbeitsblatt G 262", regulations for the use of gases from regenerative sources in public gas supply are set out. These regulations deal with the different application conditions, so that the manufacturers limit the admixing limit of hydrogen for gas turbines to 5 vol.% or even in some cases to 1 vol.%. Further regulations of G 262 state that only cavern storage facilities are suitable for storing hydrogen. If the admixture amounts to no more than 1 vol.% hydrogen by volume, all storage facilities can be used. Furthermore, a lower throughput is expected in summer months. As a result, the mixing of hydrogen and natural gas will only be possible to a limited extent, so that higher hydrogen concentrations may occur. According to DVGW regulations, hydrogen concentrations of up to 10 vol.% in the natural gas network are tolerated and up to 20 vol.% are forecast. [DBT19]

The technical data sheet DVGW G-265-3 (M) contains general requirements of hydrogen for feed-in. For the composition of hydrogen, a foreign gas content of less than 0.2 mol%, a water content of less than 50 mg/m3 for an operating pressure greater than 10 bar and a water content of 200 mg/m3 for an operating pressure less than or equal to 10 bar shall be ensured. For each plant, an installation plan is required in which all important data is entered. In addition, requirements must be made for explosion protection, since the explosion range for hydrogen is between 4 and 75.6% by volume. Instruction sheet G-262 stipulates that materials with a tensile strength of more than 800 N/mm2 should be avoided due to hydrogen-induced stress corrosion cracking.

2.3.1.2 Hydrogen Compatibility of Assets in the Natural Gas Grid

Figure 2.11 shows the hydrogen tolerances of the individual applications in different colours. A green area indicates that the hydrogen addition is harmless. If the colour changes to yellow, there is a need for adjustment and control if hydrogen-containing gases are used. However, these adjustments are technically feasible. The blue area, on the other hand, is used for applications where there is still a need for research and investigation. The influence of hydrogen is unknown here. In addition, three different admixing limits for hydrogen, of 10, 30 and 50 vol.% H_2, are defined and marked in the overview matrix. In the following, the feasibility and research needs of the three admixing ranges are discussed.

Figure 2.11: Hydrogen compatibility of natural gas infrastructure assets – taken, translated, and slightly modified from [DVG13]

Up to 10 Vol.-% H_2
The following criteria, for which there is a need for adaptation and control, are currently the limiting factor for hydrogen contents of up to 10% by volume in the natural gas network. According to "DIN 51624 - Fuels for motor vehicles", natural gas tanks currently tolerate only 2 vol.% hydrogen. Many gas turbine manufacturers currently limit the hydrogen content to 1 vol.%, otherwise the turbines may be damaged. However, solutions for higher hydrogen admixtures are available for both applications. Process gas chromatographs have problems detecting the H_2 content added. However, all measuring devices are currently being replaced, so that there is no need for action afterwards. In underground storage facilities hydrogen can promote bacterial growth and react to hydrogen sulphide. For this reason, all storage facilities must be checked individually, as each storage facility has different geological conditions. For this reason, there is still a need for research and regulation for porous storage facilities. Caverns and surface facilities, on the other hand, will tolerate hydrogen up to 10% by volume through adjustments. [DVG13]

Up to 30 Vol.-% H_2
With an admixture of up to 30% by volume there is a need for additional research and investigation, in addition to the applications already mentioned up to 10% by volume, for gas turbines, compressors, vehicle engines, forced draught burners and condensing boilers. For Stirling engines, gas cookers and CHP's there is a need for adaptation and control. For gas distribution, an admixture limit of 30% by volume is considered harmless, except for gas flow monitors, where there is merely a control requirement. The measurement and control systems can also tolerate an admixture of 30 vol.% hydrogen. However, the volume correctors are an exception, for which a research requirement is indicated. [DVG13]

Up to 50 Vol.-% H_2
Basically, the natural gas infrastructure was designed for town gas containing more than 50% hydrogen by volume. However, for admixing concentrations of up to 50% hydrogen by volume in the natural gas network, only the pressure control devices, polymer distribution pipes and the fuel cell are considered harmless. An additional need for adaptation and control is assumed for transport pipes, spherical tanks, odorization systems, steel distribution pipes, fittings and domestic installations and for all measuring and control systems, with the exception of the pressure control devices. In addition, further research and investigation needs arise regarding seals and plug connections. [DVG13]

The result is that feeding hydrogen into the natural gas network is more problematic for large customers than for the distribution network and its users. It can be assumed that a feed-in of 10% hydrogen by volume should not present any problems. In the gas distribution systems, metering systems and transport pipelines, hydrogen admixture is regarded as harmless. On the other hand, gas turbines, compressors and gas applications show great development potential. Here, however, the manufacturers themselves are in demand. Gas terminals were tested with the test gas G 222, which contains 23% hydrogen by volume. [DVG13] The analysis shows that blending up to 30% would be linked to manageable adjustments of the network infrastructure, but solutions must be found for users who have no tolerance for hydrogen or fluctuating gas compositions. This includes, for example, the glass industry, where high demands are placed on the gas quality for the burners. Possible solutions there would be the methanisation of hydrogen or gas separation using membranes.

2.3.2 Costs of the Infrastructure Adjustments

In order to quantify the costs of infrastructure adjustments for higher hydrogen compatibility, up to a complete conversion to H_2, the DVGW has carried out a survey among the gas companies. The report "DVGW G201624" compares the replacement investments that will be necessary until 2050 anyway, with the extraordinary costs of replacement investments in hydrogen-compatible assets [DVG18]. Figure 2.12 shows a timeline for upcoming investments in the gas transport network (green) and extraordinary costs for H_2 compatibility (blue).

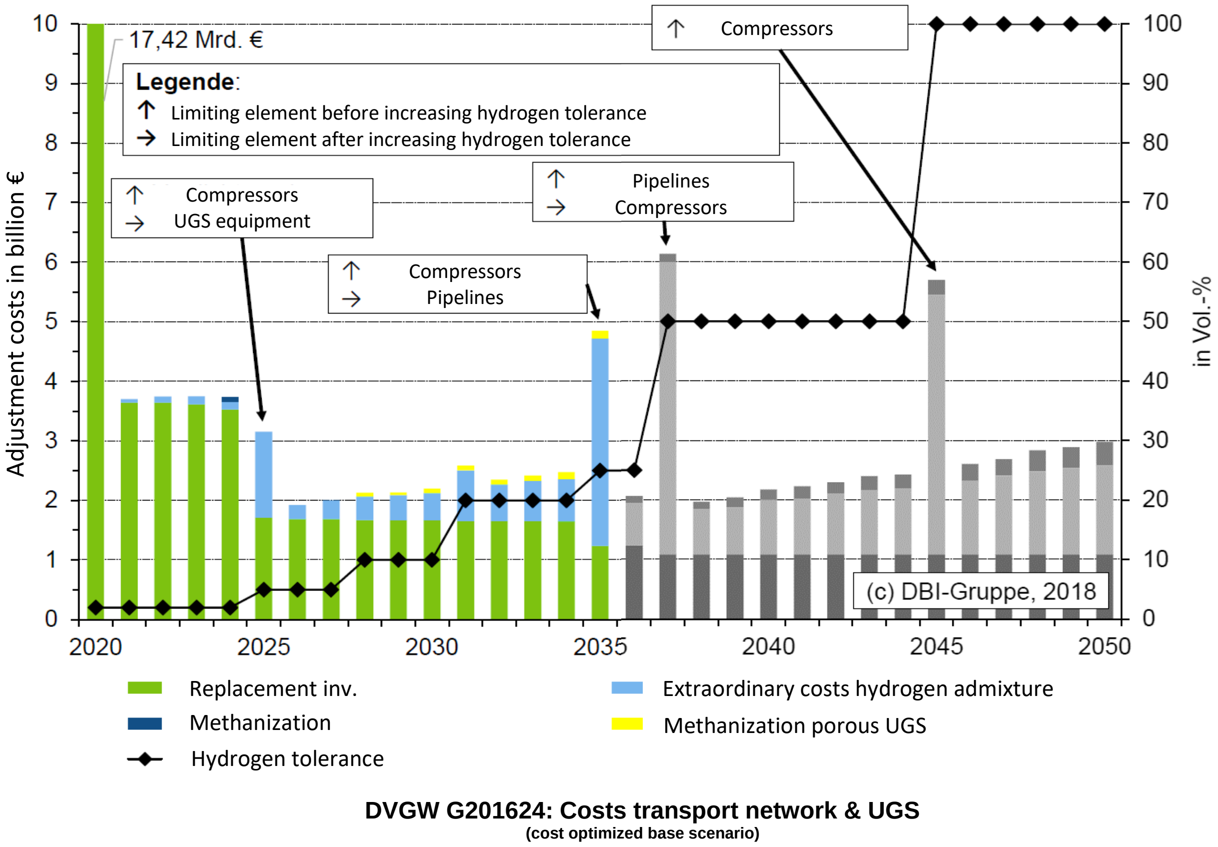

Figure 2.12: Investments and extraordinary costs for adjusting transport infrastructure and UGS to higher levels of hydrogen. – taken, translated, and slightly modified from [DVG18]

It turns out that given the 2035 timeframe, extraordinary costs of 10.7 billion € will be incurred for the transport network to achieve 25% hydrogen. An additional 3.2 billion € are necessary to increase the hydrogen tolerance of the distribution network to 50% hydrogen by 2035. This means that 10% of the 145 billion euros in replacement investments that are necessary anyway must be added to achieve 25% hydrogen compatibility in the transport network; in the distribution network this is 3.3% of the 95.5 billion euros that must be invested anyway.

According to [DVG18], a complete conversion of the natural gas network to hydrogen should take place until 2050. The extraordinary costs for this amount to 45 billion € or +23.5% of the replacement investments, if the transformation is started in 2020 as in Figure 2.12. If the start year is postponed to 2025, the costs will rise to 57 billion €. A limitation of hydrogen feed-in to 2% would result in additional costs of 110 billion € by 2050.

2.3.3 Determination of H_2 Quantities and CO_2 Savings for 2035

The compatibility studies showed that a hydrogen blending of up to 30% is feasible from a technical point of view, with moderate adjustments. The cost analysis of the DVGW also showed that a blending of 25% is possible by 2035 with additional costs of 10% of the investments in the transport network that are necessary anyway. Thus, the 25% value for the German case study is set as the target value for 2035. Table 2-14 shows the quantities of hydrogen to be fed in by 2035, based on an assumed natural gas demand of 960 TWh/a (upper calorific value), considering the increase in volume flow to maintain the energy content in the gas network due to the lower volumetric energy content and the possible CO_2 savings when using climate-neutral hydrogen.

Table 2-14: Hydrogen amounts, volume flow increase and CO_2 savings for the admixture levels 10, 25 and 50%.

hydrogen admixture level	amounts of hydrogen admixed*	total volume flow increase of mixture	CO_2 saving potential (climate neutral H_2)	CO_2 saving potential (blue H_2)
10%	27 TWh/a	7%	8 Mt/a	7.2 Mt/a
25%	75 TWh/a	21%	23 Mt/a	20.8 Mt/a
50%	191 TWh/a	53%	60 Mt/a	54.4 Mt/a

*: lower calorific value

It is shown that the chosen blending of 25% corresponds to a hydrogen quantity of 75 TWh/a or 2.25 MtH_2/a. The CO_2 savings potential is 23 $MtCO_2$/a (9.3%) when using climate-neutral hydrogen, with Norwegian blue hydrogen 20.8 $MtCO_2$/a could be avoided (NOR case study: 0.97 tCO_2/tH_2). An annual apportionment (20a, 10%) of the above-mentioned adjustment costs for 25% hydrogen leads to CO_2 avoidance costs of 65 €/tCO_2 (comparable to CCT in Option 1).

In this case study, the blending of hydrogen into the natural gas grid is mainly seen as an external event, as green hydrogen from surplus electricity is particularly suitable for feed-in, thus allowing the existing infrastructure to be used by the widely distributed producers. Initially, blue hydrogen from Norway can be fed into the natural gas pipelines leading from Norway to Germany to establish a basic admixture. In the medium to long term, Norwegian blue hydrogen will only be used to flatten the feed-in curve during periods of slack or bottlenecks. A meta-analysis of surplus electricity in 2035 revealed an average of 117 TWh of electricity that is either curtailed or can be converted into hydrogen. In a purely balance-sheet perspective, with an electrolysis efficiency of 70%, just under 82 TWh/a of hydrogen from surplus electricity would be available for feed-in. This will probably not happen due to the lack of electrolysis capacity installed by then, but constant H_2 quantities below 25% would also be possible in a grid adapted up to this value. The pure hydrogen grid developed in Option 3 would allow the blue hydrogen needed to normalise the hydrogen feed-in to be brought to the regions where it can be used to maintain the current blending value. However, these imponderable capacities are not considered in the network planning of option 3. Additionally, by using underground storage in the North (where the largest renewable capacity is installed), the injection of green gases could be normalised. An alternative would be "basic blending" of hydrogen with natural gas in Norway, so that the natural gas is already blended with a basic amount of H_2. This proportion could be adjusted to meet seasonal demands and be successively reduced as the proportion of renewable gas increases, offering a good opportunity to quickly realise higher H_2 proportions in the German natural gas network.

2.4 Option 3: Separate Hydrogen Network

In Option 3, a dedicated hydrogen network to supply industrial, mobility and heating consumers is studied and modelled. In a first step, the demands in the sectors under consideration for 2035 are examined. Subsequently, the planning and modelling of the pipeline network is described. Table 2-15 shows the constants and assumptions used for the H_2 option.

Table 2-15: Constants and assumptions for the pure hydrogen option in 2035.

constant or assumption	value	unit	source
costs of blue H_2 (production)	1.55	€/kg	NOR case study
	0.047	€/kWh	
CO_2 impact blue H_2	0.97	kgCO_2/kg	NOR case study
	0.029	kgCO_2/kWh	
costs of diesel (production)	0.0667	€/kWh	[AGO18]
CO_2 impact diesel	0.314	kg/kWh	[OEK07]
cost of natural gas (production)	0.025	€/kWh	[AGO18]
CO_2 impact natural gas	0.260	kg/kWh	[LEC05]
natural gas for grey H_2	0.2928	kgNG/kgH_2	[CAL20]
cost of grey H_2 (production)	2.07	€/kgH_2	[GRE20], [AGO18]
cost of coal	180	€/t	own assumption
cost of coking coal (production)	250	€/t	own assumption
electricity costs	55	€/MWh	own assumption
CO_2 impact electricity	267	gCO_2/kWh	own assumption
steel manufacture materials input	-	-	[WEI14]

2.4.1 Determination of hydrogen demands for 2035

In the following, the procedure for determining the H_2 demands in the sectors industry, mobility and heating is described.

2.4.1.1 Industry

For the subcategory of hydrogen producing and consuming industry, the industrial hydrogen production from the Roads2HyCom study is used and the production rates from the "merchant" and "captive" sectors are determined [ROA07]. For this purpose, a constant production quantity up to 2035 is assumed for those industrial sectors which consume or produce relevant quantities of hydrogen [NRW19]. This results in a hydrogen demand of 14.95 billion Nm³/a or 44.8 TWh /a for the hydrogen producing and using sectors of the industrial sector. The study looked at 46 company locations and added up the figures for several companies in a NUTS 3 region. The production rates of the "by-product" sector are not considered, as these are produced during a process in combination with other products. The CO_2 savings by the use of blue hydrogen amount to 93%, compared with grey hydrogen there are also monetary savings of 25%.

For the steel industry, first the plans of the steel producers were analysed. For example, Thyssenkrupp plans to inject hydrogen into the blast furnace starting in 2020 and to replace the blast furnace process by electric arc furnaces with H_2 direct reduction between 2025 and 2050. [THY19] For the German case study it is assumed that by 2035, 50% of the blast furnaces will already have been replaced, and the other half will be injecting hydrogen instead of coal into the blast furnace process.

The injection process requires 131 m³ of H_2 per tonne of pig iron, achieving CO_2 savings of up to 19% [STA19]. An annual quantity of 6.13 TWh/a is thus required for hydrogen injection at 50% of the blast furnace sites. Compared to coal injection, the injection costs are reduced by 50%.

Almost 2400 MJ or 785 Nm³ of hydrogen are required per ton of crude steel for direct H_2 reduction [WEI14]. This means that if 50% of the existing blast furnaces are converted in 2035, the hydrogen demand will be 36.76 TWh/a. When all blast furnaces have been converted by 2050, the hydrogen demand will be 73.52 TWh/a. The CO_2 savings amount to more than 80% when comparing the mass and fuel balance before and after the conversion [WEI14]. The material and energy costs (without investments) will decrease by 3% compared to the blast furnace route.

In the existing electric arc furnaces, the natural gas demand of 48 kWh per tonne of steel will be replaced by hydrogen, which corresponds to a hydrogen demand of 16 Nm³ [NAV20]. For all sites combined, this means a hydrogen demand of 0.6 TWh/a. Emissions caused by the use of natural gas are avoided by 89%, but energy costs increase by 86% in relation to natural gas costs.

In total, the steel industry will have a hydrogen demand of 43.5 TWh/a in 2035, while the demand for the whole industry sector will be 88.3 TWh/a. By using hydrogen, a total of 41.73 $MtCO_2/a$ can be avoided. The distribution of the industrial demand is shown in Figure 2.13, with a distinct industrial hydrogen cluster formation emerging.

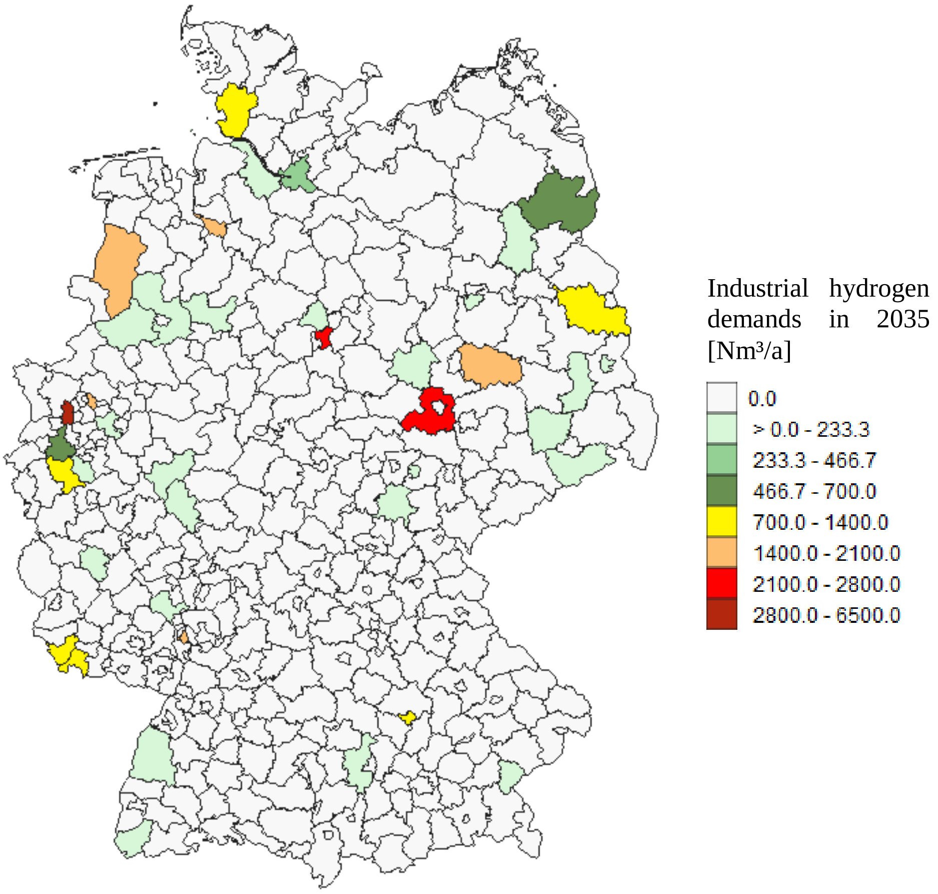

Figure 2.13: Industrial hydrogen demands in 2035.

2.4.1.2 Mobility

In the mobility sector, a distribution factor is determined for hydrogen-powered cars, buses, trains and trucks, each based on specific localised data. This includes current fleet numbers, mileage/passenger volume, fuel consumption, share of diesel vehicles, population density, government subsidies, GDP and consumer income in the region. Using forecast data from a meta-analysis and the respective calculation factors, a distribution is made at NUTS3 level.

For fuel cell passenger cars (FCEV), data from 15 studies was initially evaluated by means of a meta-study to produce a trend function. For the year 2035, this results in an FCEV share of 8.85% of the total passenger car fleet of 43.5 million vehicles. This value is allocated to the districts using a local distribution factor. The factor is made up of 25% from the proportion of mileage in the district in relation to the total mileage, whereby for FCEVs only mileage above the average of 15365 kilometres per year and vehicle are considered. An innovation factor is included in the calculation by 40%, which puts the average per capita income in the district in relation to the maximum per capita income. To 25% it is taken into account whether hydrogen filling stations already exist in the district today. The last 10% of the distribution factor takes into account the distribution of taxis among the districts. A value of 0.81 MJ/km is assumed for the H_2 consumption of cars. Thus, a total of 91.8 billion km/a are achieved with FCEVs, for which 20.7 TWh/a of hydrogen are needed. This leads to CO_2 savings of 97% compared to diesel passenger cars while reducing energy costs by 77%.

For buses, an increase in total mileage of 10.5% has been calculated by 2035, which corresponds to 2.57 billion vehicle kilometres. At the end of 2019 there were about 150 FCEV buses in Germany. A value of 900 is assumed for the predicted share of fuel cell buses in 2035, which corresponds to 2% of the total number of buses [PRO14]. With an average mileage of 57085 km per vehicle and year and a consumption of 10.27 MJ/km, this results in a hydrogen demand of 0.14 TWh/a. This value is again distributed across the districts using a distribution factor that takes into account 30% population density, 10% GDP, 20% federal financial assistance for local public transport and 40% existing FCEV buses. The hydrogen buses save 93% of the emissions of diesel buses and reduce energy costs by 47%.

For public transport trains, the first step is to determine the share of diesel-powered railcars in 2035, all of which are to be replaced by fuel cell (FC) trains. According to [BMV14], 15% of the mileage in 2030 will be achieved with diesel traction, which corresponds to 114.6 million train kilometres and is also assumed as the value for 2035. Based on local data on the mileage of trains in the NUTS 3 regions and the fuel station sites of the German railways, the mileage calculated for FC trains is distributed locally. With an energy consumption of 27.7 MJ/km, this results in a hydrogen demand for public transport trains of 0.9 TWh/a in 2035. The CO_2 savings compared to diesel trains are 97% and energy costs are reduced by 76%.

Since, due to lack of available data, rail freight transport can only be distributed at national level and not to the individual NUTS 3 regions, and since the replacement of all diesel vehicles (5.74% of total transport performance) results in a demand for H_2 of only 0.4 TWh/a, this share is further neglected.

In the case of truck freight transport, a meta-study on the forecast market share of fuel cell trucks is being carried out first. For 2035, the values of 20% share in the 3.5-7.5t size class and 2% in the 7.5-12t size class are determined from this. This results in a total hydrogen truck fleet of 61800 in 2035, which, given a total of 2.8 billion vehicle kilometres per year and an average consumption of 3.59 and 6.66 MJ/km respectively, will lead to a hydrogen demand of 2.92 TWh/a in 2035. Hydrogen trucks will reduce CO_2 emissions by 95% compared to diesel trucks and energy costs by 62%. Figure 2.14 shows the localised hydrogen demands described above, summarised for the mobility sector.

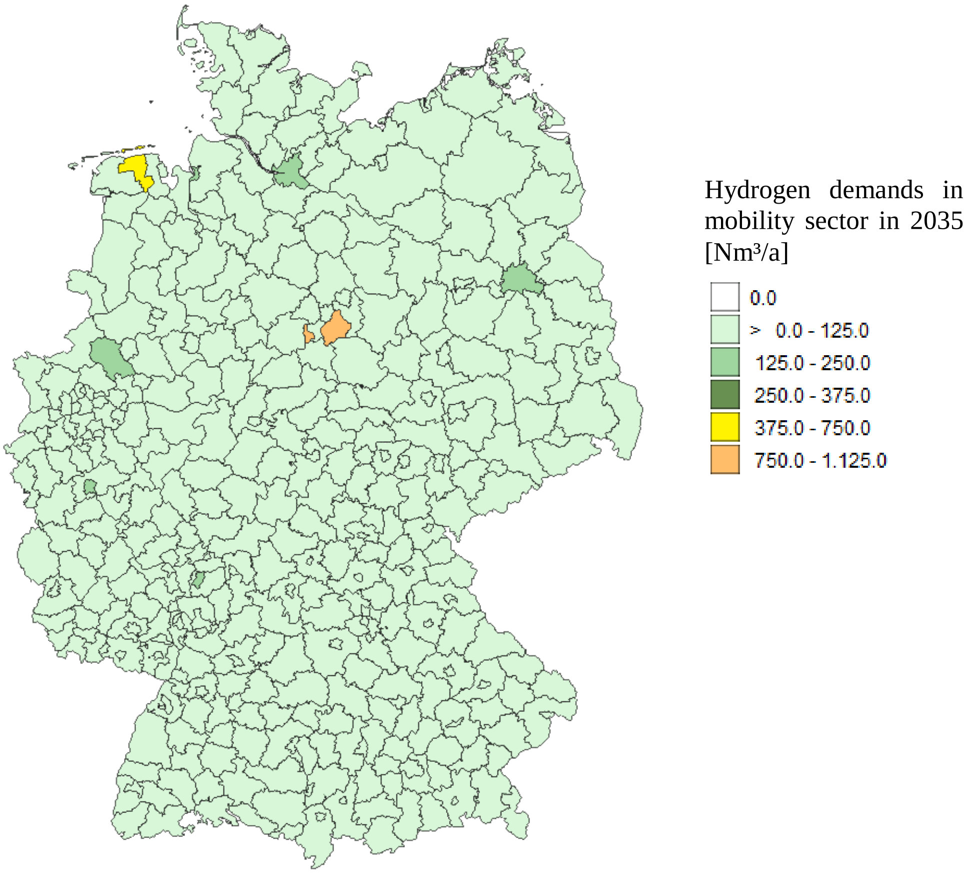

Figure 2.14: Hydrogen demands in mobility in 2035.

2.4.1.3 Heating

For the H_2 demand in the heating sector, the locations of all combined heat and power (CHP) plants are first loaded from a market data register and all plants < 50 kW are sorted out, as the focus is to be on large plants feeding into district heating networks. With an average of 4300 h/a full load hours and heat network losses of 10%, the required amount of hydrogen can be determined assuming that all existing CHPs are replaced by hydrogen CHPs by 2035. With an average lifetime of 15 years, the replacement is necessary up to that point even for very new plants, so that the hydrogen CHPs can be successively added as replacement investments over the next 15 years. The hydrogen demand is determined based on real consumption data of hydrogen CHPs from the manufacturer "2G". Figure 2.15 shows the distribution of the hydrogen demand of the CHP locations added up over the NUTS 3 regions. By switching to hydrogen CHPs, 89% of the CO_2 emissions of the previous natural gas CHPs can be avoided, but the energy costs increase by 86% compared to natural gas CHPs.

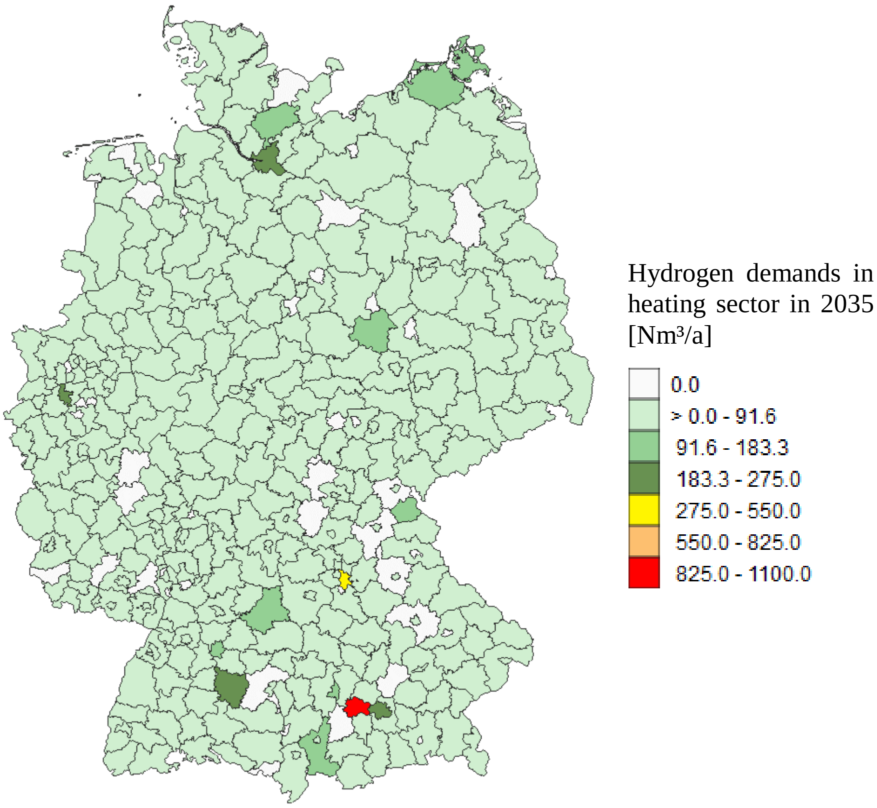

Figure 2.15: Hydrogen demands in heating sector in 2035.

The total sum of all sectors results in hydrogen demands of 140 TWh/a, and based on the data and assumptions used, the demand for the period between 2035 and 2050 is about 280 TWh/a (see Table 2-16). However, the 140 TWh/a calculated for 2035 is not the quantity to be supplied, as each region and city would have to be connected to a hydrogen network as shown in Figure 2.16. But the hotspots shown in this map account for almost half of the total demand, mainly due to the industrial demand located there.

Table 2-16: Summary of the results for the sectoral hydrogen demands.

Sector	**2035 H_2 demands**	**long term estimation**
Mobility	24.4 TWh/a	60 TWh/a
Heating	26.6 TWh/a	100 TWh/a
Industry	89 TWh/a	120 TWh/a
TOTAL	140 TWh/a	280 TWh/a

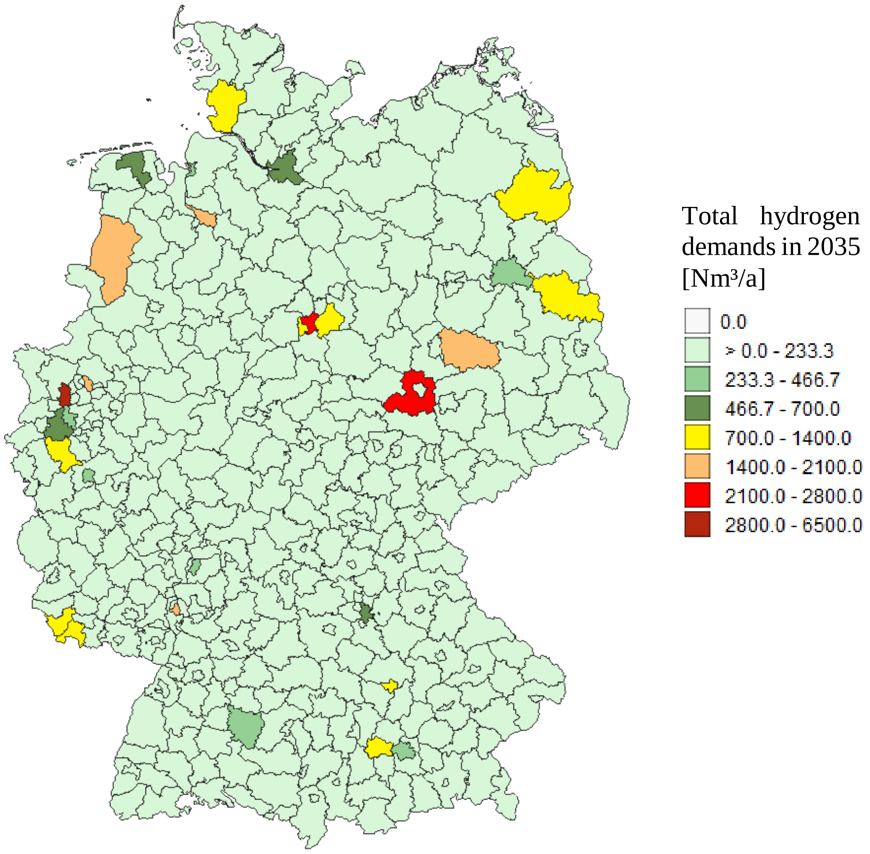

Figure 2.16: Total hydrogen demands for 2035.

The results show that the hotspots are mainly driven by industrial demand, identifying industrial hydrogen demand as the main driver for the establishment of a local hydrogen supply. The mobility and heat sectors are supplied and grow once industrial hydrogen demand has established the necessary infrastructure in a region. Figure 2.17 shows the specific and total CO_2 savings.

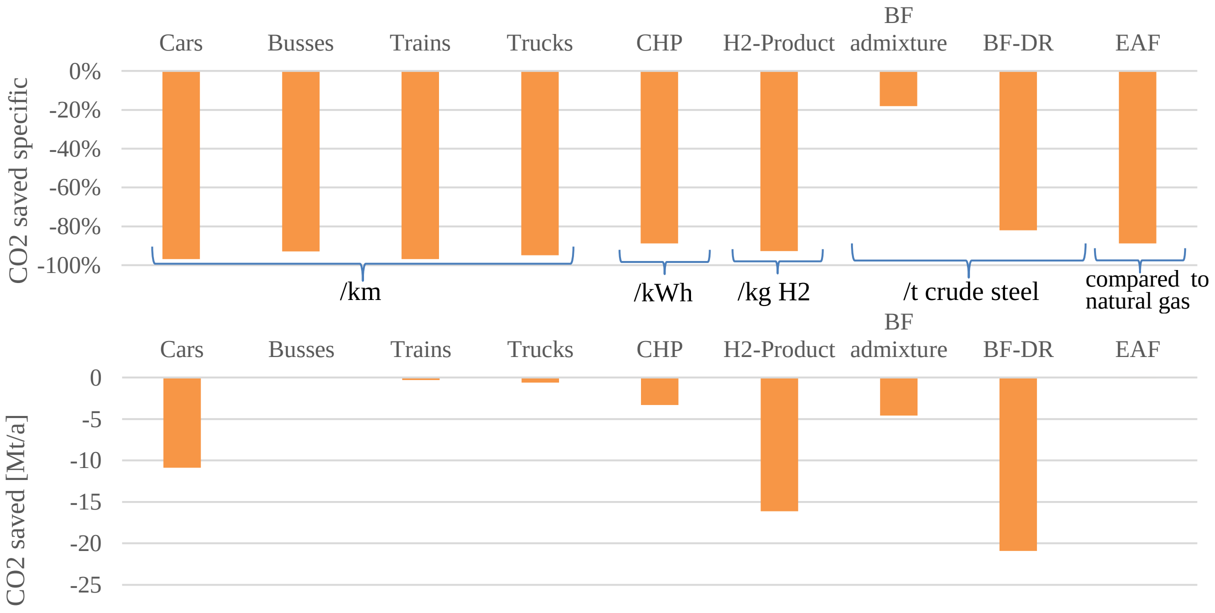

Figure 2.17: Specific (top) and absolute (bottom) CO_2-savings by use of hydrogen.

A comparison of the specific and absolute CO_2 savings in Figure 2.17 shows that the CO_2 savings per functional unit in almost every sector, apart from H_2 injection in the steel industry, are between 80 and 97% compared to the reference system. It also shows that the volume of hydrogen used in a given application has the greatest impact on the total savings. For example, the biggest savings of more than 20 $MtCO_2/a$ are possible through direct reduction in the steel industry, followed by the replacement of grey hydrogen in the H_2 industry. Passenger cars have a greater impact with over 10 $MtCO_2/a$ than the other mobile applications, as the meta-study predicted many more FCEV passenger cars than other vehicles. Table 2-17 shows the total CO_2 savings in the sectors considered, which amount to 56.9 $MtCO_2/a$ in total.

Table 2-17: CO_2 savings by hydrogen option

Sector	**CO_2 saved [Mt/a]**	**% of CO_2 in 2019**
Mobility	11.81	7.1%
Heating	3.33	2.8%
Industry	41.73	22.2%
TOTAL	56.9	7.1%

Figure 2.18 shows the specific changes in energy or material costs influenced by the use of hydrogen per functional unit.

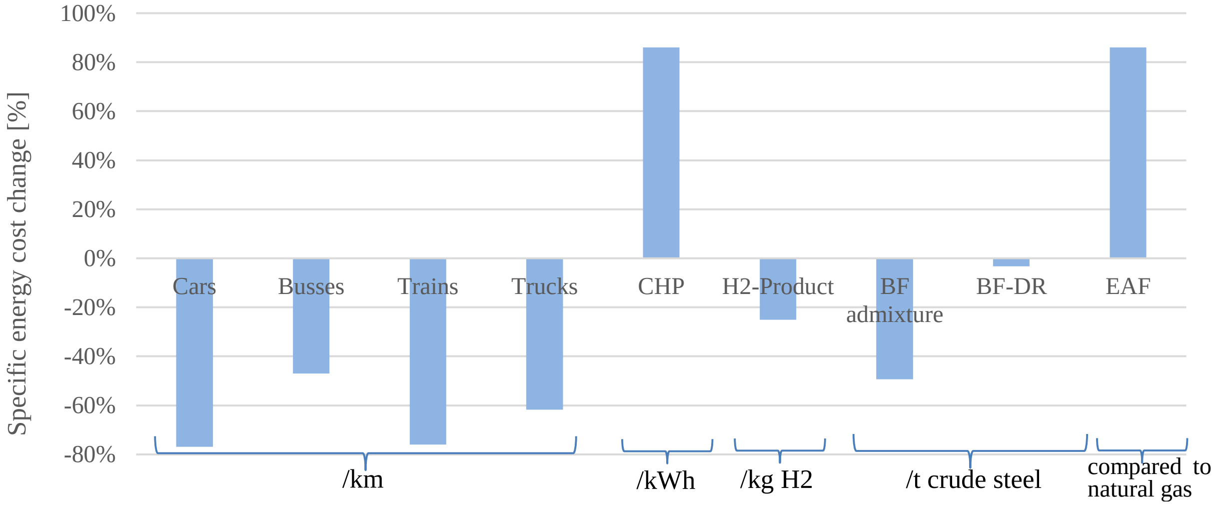

Figure 2.18: Specific energy cost change by use of hydrogen.

It is shown that wherever natural gas is directly replaced (CHP, EAF) the costs increase by over 80% compared to the reference system. This is due to the fact that natural gas is used for the Norwegian blue hydrogen, so the costs for H_2 production cannot be lower than the natural gas costs. For all other applications, specific energy cost savings of 50 to almost 80% are possible. However, since no other costs or the investments were considered in this analysis, this is particularly relevant with regard to fuel cell systems. There the investment costs (e.g. for an FCEV car) are far higher than for diesel or electric vehicles. Therefore, the energy cost differences shown here offer the opportunity to substitute the higher investments with lower operating costs beyond a certain mileage.

2.4.2 Hydrogen Pipeline System

To connect the previously identified hotspot regions, a pipeline system is planned along the course of the natural gas network. Although this case study assumes that the pipelines will be newly constructed, the rededication of existing natural gas pipelines could thus also be taken into account. When planning the route of the pipeline system, it is important to ensure that as many regions as possible are connected with as few pipeline junctions as possible. Figure 2.19 shows the route of the pipeline network that supplies all hotspots as well as the NUTS-3 regions with hydrogen on the way between the hotspots. Thus, 113 TWh/a, or more than 80% of the total demand in Germany which was calculated before, can be covered. The hotspots account for more than 70 TWh/a.

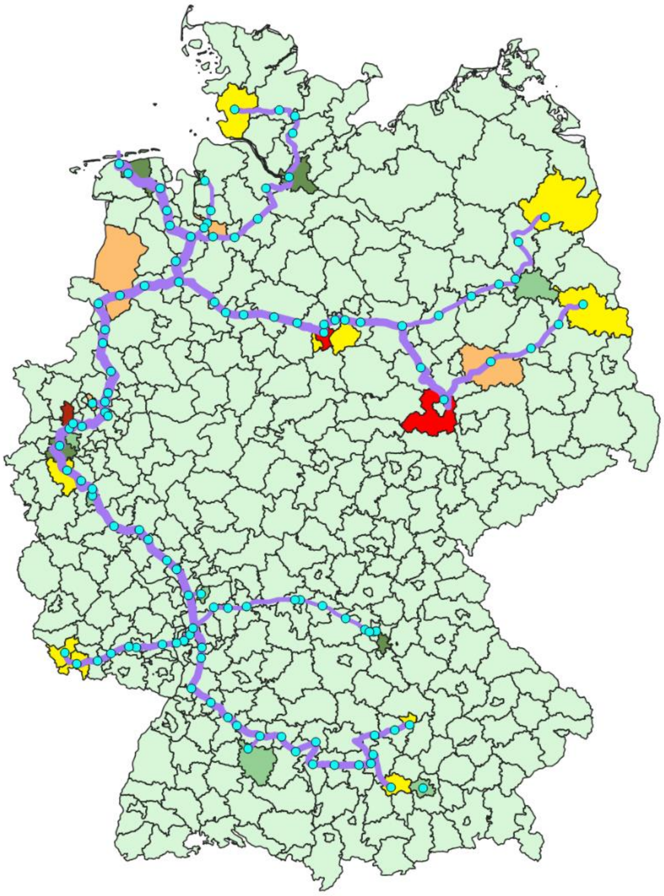

Figure 2.19: Hydrogen network connecting hot spot areas and the regions in between.

The map shows in purple the course of the pipeline network, the turquoise points represent so-called distribution centres in the respective connected districts, from which the hydrogen is distributed further within the district. However, this level is not considered in any deeper detail in the study. Table 2-18 shows the material data and constants used for the pipeline transport of hydrogen. The density is only the starting value, since it changes with increasing pressure losses without recompression, depending on the pressure in the pipeline.

Table 2-18: Constants for H_2 pipeline transport

Pipeline inlet pressure	Pipeline min. pressure	Pipeline inlet temperature	Pipeline average temperature	density (ρ)	dyn. viscosity (η)	Roughness of pipeline (ε)
[bar]	[bar]	[°C]	[°C]	[kg/m³]	[x10^{-6} Pa·s]	[m]
100	30	15	15	7.926	8.95645	0.0000417

For modelling H_2 pipelines, the same generally valid equations and assumptions are used as for CO_2 pipelines (diameter and pressure losses, see 2.2.2.1). For the investment costs of the pipelines, an average value from two cost functions is used. As the first cost function, the Parker function is used again, since it was originally developed for the calculation of H_2 pipelines [KNO15]:

$$I_{pipeline,Parker} = (996820 \cdot D^2 + 441912 \cdot D + 223522) \cdot L + 545537$$

with: $I_{pipeline,Parker}$: investment costs pipeline [$€_{2010}$]; D: inner diameter pipeline [m]; L: pipeline length [m]

As second function, an exponential function from Mischner is used, which includes the costs for natural gas pipelines with a 5% mark-up for H_2 compatibility [REU19]:

$$I_{pipeline,Mischner} = L \cdot 292.152 \cdot e^{0{,}0016 \cdot \frac{D}{mm}}$$

with: $I_{pipeline,Mischner}$: investment costs pipeline [$€_{2010}$]; D: inner diameter [mm]; L: pipeline length [m]

An average of 5 €/(m·a) (Mischner) and 2.5% of the investment costs (Parker) is used for operating costs [REU19], [KNO15]. For the annuity of the investment costs, a calculatory lifetime of 40 years is used at an interest rate of 10%.

For the investment costs of hydrogen compressors, an equation from [REU19] is used, which consists of basic costs of 15000 € per kW with a scaling factor of 0.6089:

$$I_{compressor} = \frac{15000€}{kW} \cdot P^{0.6089} \cdot f_{inst}$$

with: $I_{compressor}$: investment costs compressor [€]; P: compressor power [kW]; f_{inst}: 2.5 for pipeline compression

For the operating costs, 5% of the investment is assumed, the calculatory lifetime of compressors is assumed to be 20a, the interest rate is 10%. Thus, during the assumed life of the pipeline system of 40 years, after half of the time a replacement investment of the compressor is necessary.

For the calculation of the required compression energy the equation used for CO_2 compression in chapter 2.2.1 is used. For a compression from 30 to 100 bar at a temperature of 15°C the energy required is 0.505 kWh/kgH_2, the compressor power to be installed is 0.0576 kW/(t·a).

It is assumed that the hydrogen from Norway arrives at the German transfer station at 15°C and 30 bar, which makes initial compression essential. According to the assumptions on compressors described above, the annual H_2 supply of 113 TWh/a (3.4 Mt/a) will cost 3.09 ct/kgH_2.

Since the density of gaseous H_2 is 100 times lower than the density of the quasi-liquid CO_2 transported in Option 1, higher pipeline and compression costs are to be expected. For this reason, different variants are calculated in advance for the pipeline network shown in Figure 2.19, in order to find the optimum ratio of boosters to pipeline diameter. Figure 2.20 shows that if there is more than the one initial recompression (due to the pressure losses caused by transport to Germany), the annual costs (combined investment, operating and energy costs) increase with each additional recompression. There is no benefit, as with the CO_2 option, from the reduction of the pipe diameter with more frequent recompression. Therefore, the German hydrogen pipeline network does not require any further post-compression, but a minimum pressure of 30 bar must be maintained throughout the network. Thus, each segment now transfers its end pressure to the subsequent segment, the density is also adjusted to the new inlet pressure in the subsequent segment.

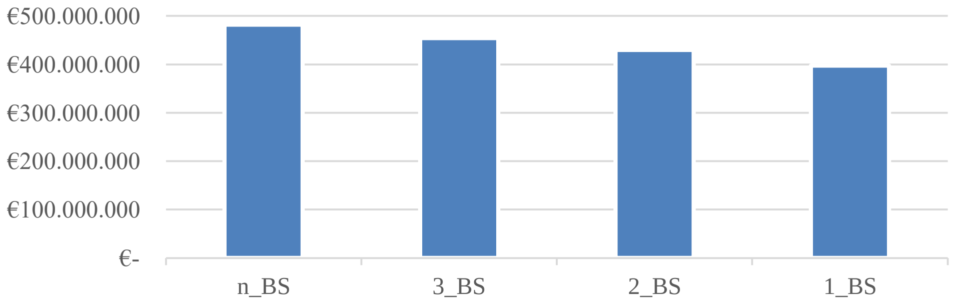

Figure 2.20: Annual costs für variating number of recompressions (n=no limit)

For the design and optimisation of the individual pipeline sections, again a solver is used that works under the following boundary conditions: The transport velocity can be varied between 0.1 and 10 m/s, the pressure losses per km are limited to 0.08 bar/km and the Δpmax per section to 5 bar. This leads to a solution without the need for further recompression and pure transport costs of 8.1 ct/kgH_2 (5% of the manufacturing costs). Including the initial recompression from 30 to 100 bar, this results in costs of 11.19 ct/kgH_2 (7.3% of manufacturing costs). Figure 2.21 shows the pipeline network, coloured by transport costs per section.

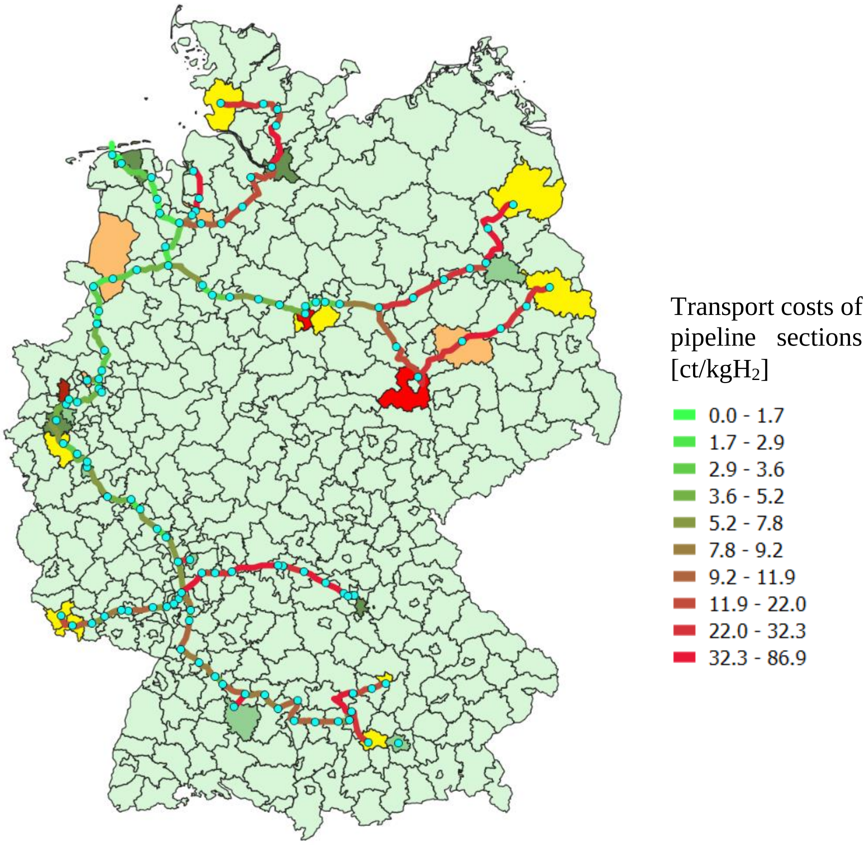

Figure 2.21: Hydrogen pipeline network coloured by costs of segments.

Table 2-19 shows the minimum, maximum and average values for transport costs and diameter of the 2653 km long pipeline system.

Table 2-19: Minimum, maximum and average values for costs and diameter in the hydrogen pipeline network

transport costs of segments [ct/kgH_2]	
Min	0.72
Max	86.89
Average	13.08

inner diameter of pipeline segments [m]	
Min	0.168
Max	1.152
Average	0.564

Figure 2.22 shows the annual costs for the pipeline system and the compression at the transfer station. It can be seen that the energy costs for the compression correspond to almost 40% of the annual apportionment of the pipeline system investment, which again shows that further compression would not be economically viable.

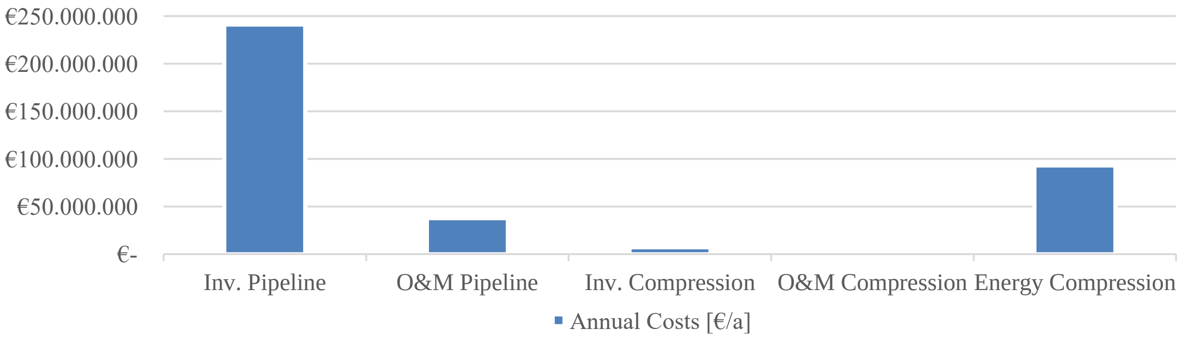

Figure 2.22: Annual costs of hydrogen pipeline system and compression

Due to the electricity demand for compression, 0.45 MtCO_2/a are emitted annually, corresponding to the German electricity mix (267 gCO_2/kWh). This leads to emissions of 0.13 kgCO_2/kgH_2 when applied to the amount of hydrogen transported. This increases the CO_2 factor of Norwegian blue hydrogen from 0.97 kgCO_2/kgH_2 to 1.1 kgCO_2/kgH_2. The CO_2 savings from the use of blue hydrogen are reduced from 56.9 MtCO_2/a to 56.45 MtCO_2/a.

2.5 Technical Best-Case Option

For the technical best-case option, the best of the three options previously outlined should be brought together in a feasible combination. Therefore, the central results of the three options are first summarised briefly.

- **Option 1:** 50.7 Mt CO_2/a are captured and can be transported for 7.34 €/tCO_2 via pipeline or 13.57 €/tCO_2 via ships; assuming additional storage costs of 2 €/tCO_2; 48.65 Mt CO_2/a can be abated for average costs of 70.5 €/tCO_2 (incl. pipeline & storage)
- **Option 2:** 25% hydrogen in NG-network can save 23 Mt CO_2/a; H_2 Transport costs for 75 TWh/a: 0.67 €/kgH_2; CO_2 avoidance costs by infrastructure adjustments: 65.37 €/tCO_2
- **Option 3:** 56.45 Mt CO_2/a can be saved by hydrogen in mobility, heating and industry; H_2 Transport costs for 113 TWh/a: 0.11 €/kgH_2 (@1.55 €/kg H_2 production costs); in most cases, the pure energy and raw material costs are substantially decreased (except where natural gas is directly substituted)

Current political efforts regarding hydrogen in Germany result in the two hydrogen options (2&3) being adopted without any need for adjustments. The demand covered by the pipeline system in

2035 is 113 TWh/a, which fits very well into the picture compared with the values from the German hydrogen strategy (90 to 110 TWh/a in 2030) [BMW20].

Since the retrofitting of existing natural gas pipelines is not covered primarily in this case study, but in the current discussion is seen as the most likely way to establish a pure hydrogen network, this aspect will be briefly touched on in the following. Since the hydrogen pipelines considered in option 3 follow the natural gas network and no further compression is planned apart from the first recompression at the transfer station, only the pipelines themselves are considered to be retrofitted. In this case study, the pure pipeline investment costs for the transport of 3.35 MtH_2/a over 2653 km amount to 2.36 billion €. According to the study "European Hydrogen Backbone", the retrofit costs amount to 10 to 35% of the costs of building new hydrogen pipelines. Thus, using the average value, the costs would be reduced by 22.5% to 531 million €. [WAN20] Assuming the same operating costs, this would lead to specific transport costs without compression of 2.74 ct/kgH_2 or 5.83 ct/kgH_2 including recompression at the transfer station. However, in this case study, the diameters of the individual pipeline segments were specially adapted to the needs in the regions supplied, which is why the costs would probably be higher due to larger diameters in the natural gas network. For example, the backbone study assumes a constant diameter of 48 inches (1.22 m), the maximum inside diameter of the pipes used here is 1.15 m, the average is 0.56 m.

A hydrogen admixture of more than 30% in the natural gas grid is not regarded as sensible due to compatibility problems, the next sensible step would therefore probably be a complete conversion to 100% hydrogen.

The CO_2 option cannot be simply adopted, as the sources that now use blue hydrogen from Norway under option 3 (H_2 SMR, refineries, ammonia and steel production) are excluded from the analysis. This leaves only sources from paper & cement production as well as waste incineration and the two cheapest refinery sites (stacks). To still have a relevant effect on greenhouse gas reduction, the lower limit for CCS sites is lowered from 250 kt/a to 100 kt/a. This means that 25.4 $MtCO_2/a$, which is half the amount of CO_2 from option 1, can still be captured for less than 70 €/tCO_2. The shipping solution for CO_2 transport was chosen because it reduces the potential for regulatory and acceptance problems by reducing infrastructure development, and because less new infrastructure needs to be built for a bridging technology like CCS. However, a total of 1700 km of pipelines will be used to connect the CO_2 sources within a 50 km radius of the 36 loading terminals. To transport the CO_2 to the Netherlands, 11 ships, whose capacity has now been increased to 78 $ktCO_2$, make a total of 85 trips per year. This results in transport costs of 16.43 €/tCO_2. Gaseous transport at 30 bar in the CO_2 network has also been considered, but it is not cost-effective due to higher pipeline and liquefaction costs (110 bar is 13% cheaper). Including conditioning and unloading at the storage site, the total costs are 17.29 €/tCO_2. Figure 2.23 shows the new ship loading stations and the connected sources and pipelines.

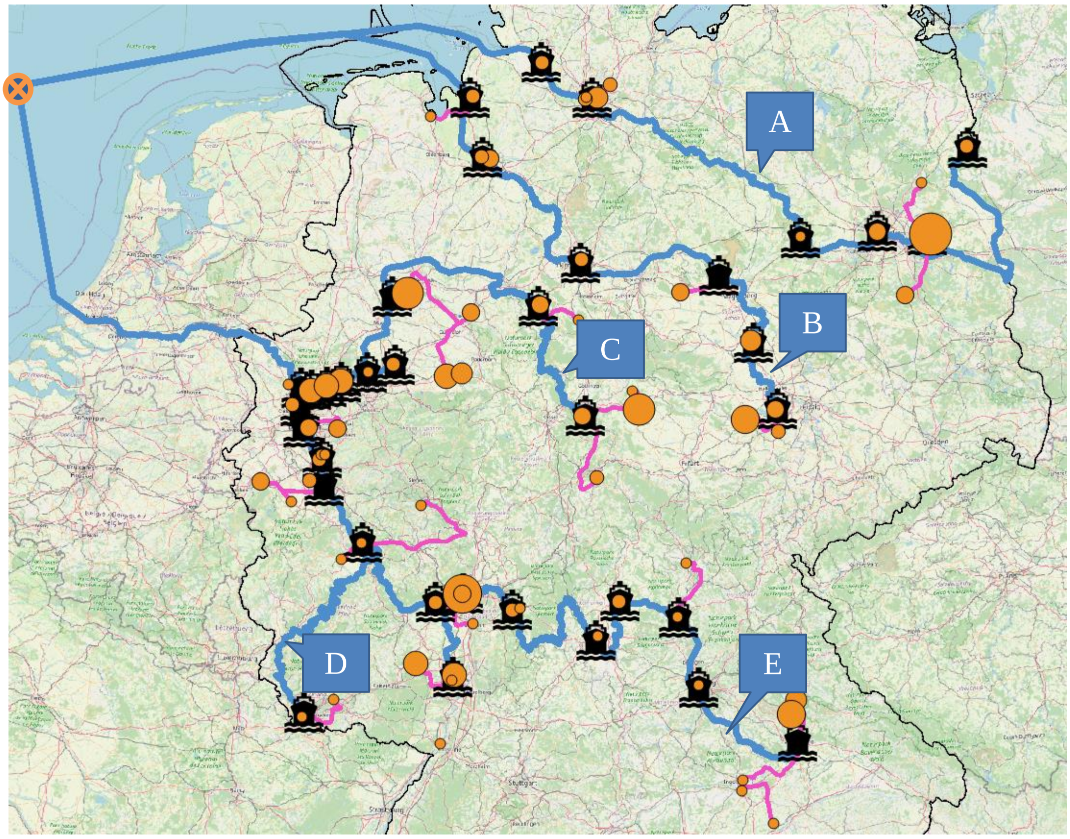

Figure 2.23: Ship routes (blue), CO_2 sites (orange), loading stations (black) and CO_2 pipelines (pink) in the best-case option. Map in background © OpenStreetMap contributors

The specific transport costs of 16.43 €/tCO_2 are about 4 Euros higher than for the ship variant in Option 1, as many more small sites are now connected and therefore more infrastructure is needed. The transport emits 0.59 MtCO_2/a, which must be deducted from the 22.983 MtCO_2/a avoided. Thus, 22.4 MtCO_2/a can still be avoided by CO_2 separation in the best-case. Including the two hydrogen options adopted in the best-case, this results in over 100 MtCO_2/a that can be avoided (see Figure 2.24). This corresponds to 12.5% of Germany's greenhouse gas emissions in 2019.

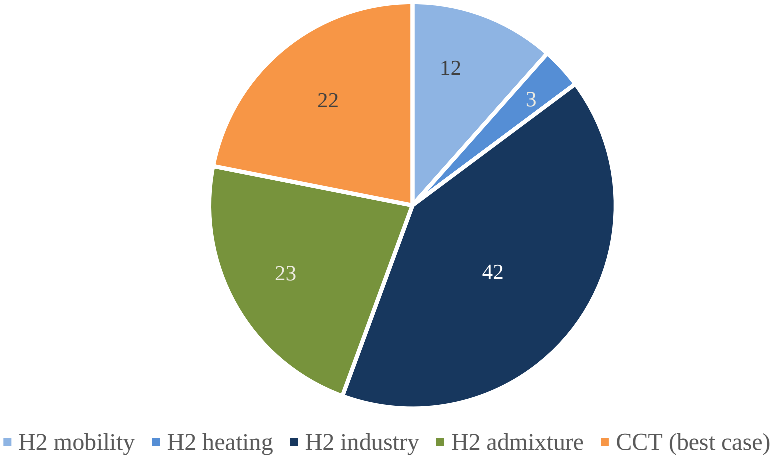

Figure 2.24: CO_2 avoidance in the best-case option in Mt/a (sum: 102.27)

Figure 2.25 shows the combined infrastructure of the best-case option in one map.

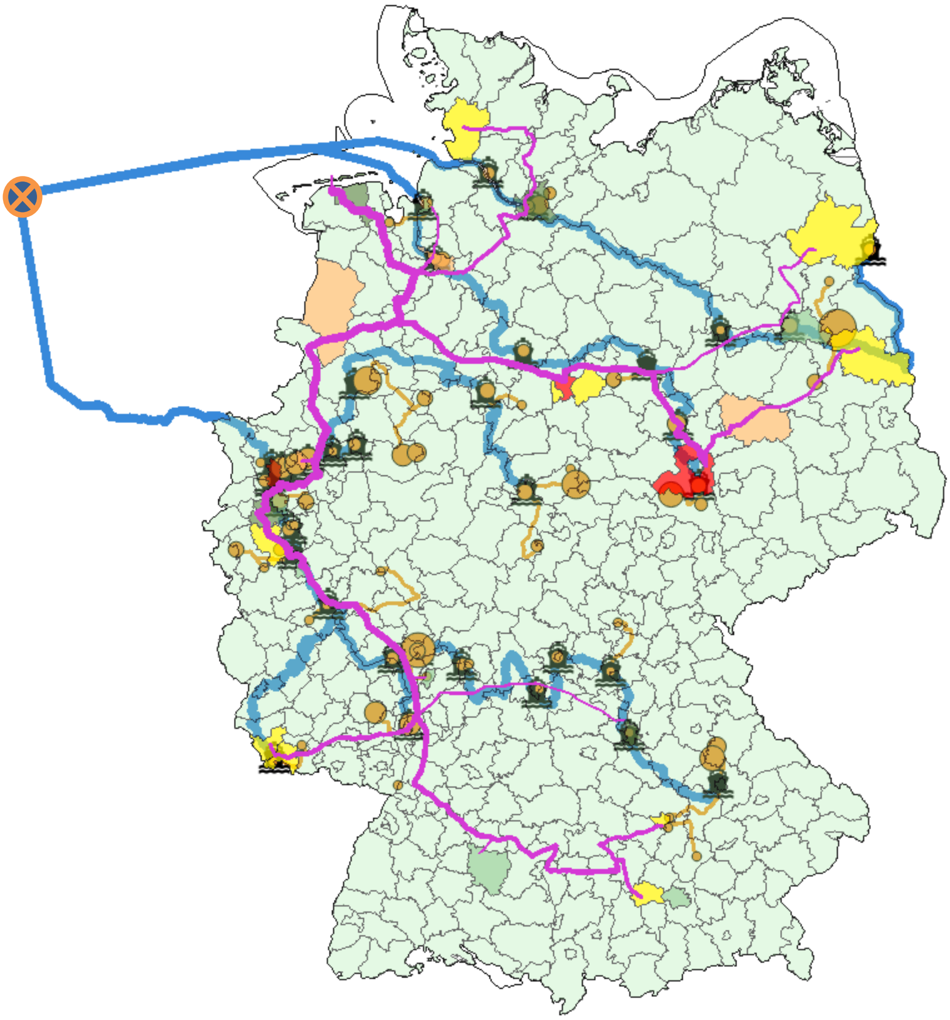

Figure 2.25: Best-case option with hydrogen demands of NUTS3 regions, hydrogen pipeline (pink), waterways for CO_2 ship transport (blue), CO_2 sites and pipelines (orange) and CO_2 loading sites (black ship symbols).

2.6 Conclusions

In the following, the most important key messages from the technical part are summarized as bullet points:

- CO_2 transport costs at least double while using ships instead of pipelines
- But: A CO_2 pipeline system could face more acceptance and regulatory issues than ships
- CCS clusters lower costs due to scale effects of the transport infrastructure
- Hydrogen admixture of 25% is, relative to the transported hydrogen, more expensive than a new built pure hydrogen network: 0.67 €/kgH_2 (at 75 TWh/a admixture) to 0.11 €/kgH_2 (at 113 TWh/a pure hydrogen) because assets of the whole network have to be adjusted
- For pure hydrogen pipelines, further recompression within the network should be avoided to lower costs
- Industry is the main driver for hydrogen in other sectors in the surrounding regions
- In terms of energy and raw materials, most hydrogen applications are cheaper than the replaced technology, which offers the chance to compensate for the higher investment costs, especially in fuel cell applications

2.7 References

[ACO14] Acomi, N.; Acomi, C.A: *The influence of different types of marine fuel over the energy efficiency operational index. In: Energy Procedia 59, pp. 243 – 248. 2014.*

[AGO18] Agora Verkehrswende, Agora Energiewende and Frontier Economics (ed.): *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*. 2018.

[BAT13] Remus, R. et al.: *Best Available Techniques (BAT) Reference Document for Iron and Steel Production*. 2013.

[BMV14] Bundesministerium für Verkehr und digitale Infrastruktur (ed.): *Verkehrsverflechtungsprognose* 2030. 2014.

[BMW20] Federal Ministry for Economic Affairs and Energy (ed.): *The National Hydrogen Strategy*. 2020.

[DBT18] Wissenschaftlicher Dienst des Bundestages (ed.): *Energieverbrauch bei der Produktion von mineralischem Stickstoffdünger*. 2018.

[DBT19] Wissenschaftlicher Dienst des Bundestages (ed.): *Grenzwerte für Wasserstoff (H2) in der Erdgasinfrastruktur*. 2019.

[CAL20] Caloric.com: *Wasserstoff aus Dampfreformierung*. URL: https://www.caloric.com/de/product/wasserstoffechnologie/wasserstoff-aus-dampfreformierung/. 2020.

[CLU19] Kather, A. et al.: *Endbericht des Teilprojekts CLUSTER – TUHH: Definition der CO2-Quellen, Quellenbilanzierung, Interaktion Quelle/Transportnetz, Schiffstransport*. 2019.

[DES18] Destatis (ed.): *Produzierendes Gewerbe – Düngemittelversorgung*. 2018.

[DNV10] Det Norske Veritas (ed.): *Global Technology Roadmap for CCS in Industry - Sectoral Assessment: Refineries*. 2010.

[DVG13] Deutscher Verein des Gas- und Wasserfaches e.V. (DVGW) (ed.): *Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz*. 2013.

[DVG14] Deutscher Verein des Gas- und Wasserfaches e.V. (DVGW) (ed.): *Merkblatt DVGW G265-3 (M)*. 2014.

[DVG18] Deutscher Verein des Gas- und Wasserfaches e.V. (DVGW) (ed.): *Transformationspfade zur Treibhausgas-neutralität der Gasnetze und Gasspeicher nach COP 21*. 2018.

[ELE18] Element Energy (ed.): *Shipping CO2 – UK Cost Estimation Study*. 2018.

[FAR95] Farla, J. et al.: *Carbon Dioxide Recovery from Industrial Processes*. 1995.

[GFC19] NAVIGANT (ed.): *GAS FOR CLIMATE – The optimal role for gas in a net-zero emissions energy system*. 2019.

[GRE19] Sun, P. et al.: *Updates of Hydrogen Production from SMR Process in GREET®*. 2019.

[GRE20] Greenpeace Energy EG (ed.): *Blauer Wasserstoff*. 2020.

[HEK09] Hektor, E.A. et al.: *Reduction of Greenhouse Gases in Integrated Pulp and Paper Mills: Possibilities for CO2 Capture and Storage*. In: Clean Technologies and Environmental Policy. 2009.

[IEA05]: IEA Greenhouse Gas R&D Programme (IEAGHG) (ed.): *Building the Cost Curves for CO2 Storage: European Sector*. 2005.

[JRC11] European Commission Joint Research Centre (JRC) (ed.): *Technical and Economic Characteristics of a CO2 Transmission Pipeline Infrastructure*. 2011.

[KNO15] Knoope, M.: *Costs, Safety and Uncertainties of CO2 Infrastructure Development*. 2015.

[KUP19] Kuparinen, K. et al.: *Biomass-based Carbon Capture and Utilization in Kraft Pulp Mills*. In: Mitigation and Adaptation Strategies for Global Change. 2019.

[KUR11] Kuramochi, T. et al.: *Comparative Assessment of CO2 Capture Technologies for Carbon-intensive Industrial Processes*. In: Progress in Energy and Combustion Science 38, pp. 87-112. 2011.

[LEC05] Lechtenböhmer, S. et al.: *Treibhausgasemissionen des russischen Erdgas-Exportpipeline-Systems*. 2005.

[MAL13] Mallon, W. et al.: *Costs of CO2 Transportation Infrastructures*. In: Energy Procedia 37, pp. 2969-2980. 2013.

[NAV20] NAVIGANT (ed.): *Energiewende in der Industrie - Branchensteckbrief der Eisen- und Stahlindustrie*. 2020.

[NRW19] Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen (ed.): *Wasserstoffstudie Nordrhein-Westfalen*. 2019.

[OEK07] Öko-Institut e.V. (ed.): *Endenergiebezogene Gesamtemissionen für Treibhausgase aus fossilen Energieträgern unter Einbeziehung der Bereitstellungsvorketten*. 2007.

[PEL18] Peletiri, S. et al.: *CO2 Pipeline Design: A Review*. 2018. In: Energies 11, 2184. 2018.

[PRO14] Prognos AG (ed.): *Entwicklung der Energiemärkte – Energiereferenzprognose*. 2014.

[REU19] Reuß, M.E.: *Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur*. In: Energie & Umwelt / Energy & Environment 476. 2019.

[ROA07] Roads2HyCom (ed.): *DELIVERABLE 2.1 AND 2.1a "European Hydrogen Infrastructure Atlas" and "Industrial Excess Hydrogen Analysis" - PART II: Industrial surplus hydrogen and markets and production*. 2007.

[ROU16] Roussanaly, S. et al.: *Techno-economic analysis of MEA CO2 capture from a cement kiln – impact of steam supply scenario*. In: Energy Procedia 114, pp. 6229-6239. 2016.

[STA19] DVS Media GmbH (ed.): *Wasserstoff statt Kohle für eine klimafreundliche Stahlproduktion*. In: STAHL+TECHNIK 6, pp. 74-74. 2019.

[THY10] Thyssenkrupp AG (ed.): *Zwei Technologiepfade – ein Ziel*. In: Compact Steel 01, pp. 14-15. 2019.

[VCI17] Verband der Chemischen Industrie e.V. (VCI) (ed.): *Chemiewirtschaft in Zahlen*. 2017.

[VDZ08] Verband deutscher Zementwerke (VDZ) (ed.): *Änderungen der europäischen Richtlinie zum Emissionshandel: Auswirkungen auf die deutsche Zementindustrie*. 2008.

[WAN20] Wang, A. et al.: *European Hydrogen Backbone*. 2020.

[WEI14] Weigel, M.: *Ganzheitliche Bewertung zukünftig verfügbarer primärer Stahlherstellungsverfahren*. 2014.

[WIK20] Wikipedia.de: *Harnstoff*. 2020. URL: https://de.wikipedia.org/wiki/Harnstoff.

[WVS16] Wirtschaftsvereinigung Stahl (WVS) (ed.): *Fakten zur Stahlindustrie*. 2016.

[YOU18] You, F.; Tang, Y.: *Multicriteria Environmental and Economic Analysis of Municipal Solid Waste Incineration Power Plant with Carbon Capture and Separation from the Life-Cycle Perspective*. In: ACS Sustainable Chem. Eng. 6, 937–956. 2018.

3 MACROECONOMIC PERSPECTIVE AND RESULTS

3.1 The macroeconomic approach

3.1.1 Objectives and approach

To successfully mitigate climate change, a decarbonisation of the energy system is key and helps to accelerate the transformation towards a low-carbon economy and society. For a deep decarbonisation, energy production and consumption must change significantly. A shift from fossil fuels to GHG-neutral energy carriers is required. Such an energy system transformation is unavoidable and accompanied by substantial changes of the energy infrastructure. Large-scale energy infrastructure projects are long-term and require extensive investment and policy decisions made today [HOF20a]. The primary objective of the macroeconomic approach is to assess the conditions that foster or hinder the successful implementation of a German H2/CCS infrastructure. The three infrastructure options of the German case study are evaluated in terms of their feasibility. To do so, a qualitative scenario and stakeholder analysis considering economic and non-economic aspects is used. The macroeconomic analysis consists of two parts. In part one, six qualitative socio-technical scenarios were developed, that function as an evaluation framework for the infrastructure options. Part two consists of an interdisciplinary scenario-based evaluation of the three infrastructure options[5]. Within the German case study, the macroeconomic approach has a special role as it provides the framework for the interdisciplinary infrastructure evaluation and brings together the individual disciplines' results.

The macroeconomic approach is based on the assumptions derived from complexity economics, which understands the economy as a complex adaptive system. A complex adaptive system is described as a dynamic network of heterogeneous agents who adjust their behaviour according to their interactions with others. In complex adaptive systems, such as energy system, it is hardly possible to identify and implement optimal policies through central planning [ROO15].

Applied to ELEGANCY, it implies that large-scale infrastructure projects which affect the society as a whole, cannot be successfully implemented in a democracy and market economy by the political decision of a central planner. The decision for and implementation of large-scale project depends on the various individual decisions made by different actors who have different and often conflicting interests. According to Roos, heterogeneous agents take economic and non-economic aspects that are both rational and irrational into account when evaluating different infrastructure options [ROO07]. This perspective underlines the decentral nature of decisions, making successful planning even more complex.

Policies which are optimal from a narrow economic perspective are not per se the best solution for society. By concentrating on a single discipline's perspective, policy recommendations often neglect crucial aspects that are important for the implementation. Furthermore, they are based on expectation about future developments. The future is, however, characterized by major uncertainties related to a high level of complexity and thus hardly predictable. Consequently, optimal recommendations might not be selected by decision-makers or fail when it comes to the implementation. Considering the urgency related to climate change, this failure might have fatal consequences.

A shift to a more holistic assessment of energy systems as a complex adaptive system is necessary and implies to include (1) complexity, (2) non-economic aspects, (3) uncertainty, (4) stakeholders [HOF20a]. The approach's underlying understanding of feasibility is based on Schubert et al. [SCH15]. For the context of ELEGANY, Schubert's conceptual framework of energy scenario

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[5] The process of qualitative scenario development as well as the results of the scenario analysis are published in Hoffart et al. [HOF20a] which represents the base for this report.

analysis was adapted and applied to a policy context. Political feasibility is key for a successful energy system transformation and can be distinguished into two subsequent steps. The first step includes the political process of decision-making and finding majorities which is characterized by regulatory and legislative efforts. In a second step, the process of implementation is crucial and requires financial and personnel resources to translate policies into practice.

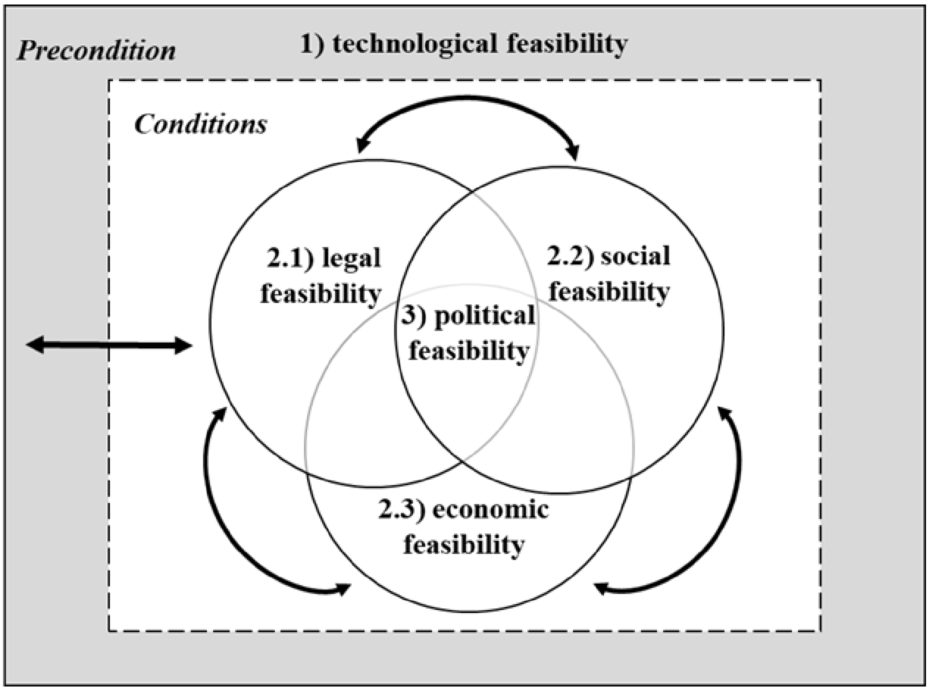


Figure 3.1: Analysis framework to identify feasible policies.
Source: Hoffart et al. (2020a).

To be more precise, Figure 3.1. shows the different conditions and preconditions of political feasibility and its interdisciplinary components. Technological feasibility represents the first level and can be understood as a necessary precondition for feasible energy policies. Without any sophisticated technological measures, no energy policy can be implemented. It implies that when it comes to decisions on energy policies related technologies are already available. The second level of political feasibility is shown by the inner box which comprises legal, social and economic feasibility. These conditions influence each other and are interrelated with the technological feasibility. Economic incentives, legislative efforts or the provision of governmental resources to facilitate social convergence constitute necessary conditions. Therefore, given the technological precondition are met, political feasibility is defined as the overlap of all level three conditions.
The concept of political feasibility marks the cornerstone of the scenario approach and comprises all four disciplines of the German case study. The following section describes the method of qualitative scenario and the approaches different steps in more detail.

3.1.2 Method and process

The method of qualitative scenario analysis has its origin in the academic field of future studies [BIS07,5]. Although there is no uniform definition for a scenario in the academic literature [BRA05,796], scenarios can be described as “a possible situation in the future, based on a complex network of influence factors” [GAU89,115]. In this sense, scenarios “reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play” [KOS08,12]. From a methodological perspective, scenario analysis is a tool and thought experiment to explore how the future might look like. Qualitative scenarios differ from quantitative prognosis and forecasting methods in the sense that they do not aim to accurately predict the future, nor to be self-fulfilling or complete. Instead, they explore a wide range of plausible future developments without assigning probabilities [GRU02]. Thus, qualitative scenario development is a tool to deal with high level of complexity and uncertainty. Furthermore, it allows to include different disciplines perspectives and feedback from different stakeholders, which is a key feature of the German case study of ELEGANCY.

The development of qualitative scenarios consists of several phases. Depending on the used approach, the number of phases and the related steps can vary [BRA05]. For the development of qualitative scenarios in the German ELEGANCY case study, four separate phases can be described (see Figure 3.2).

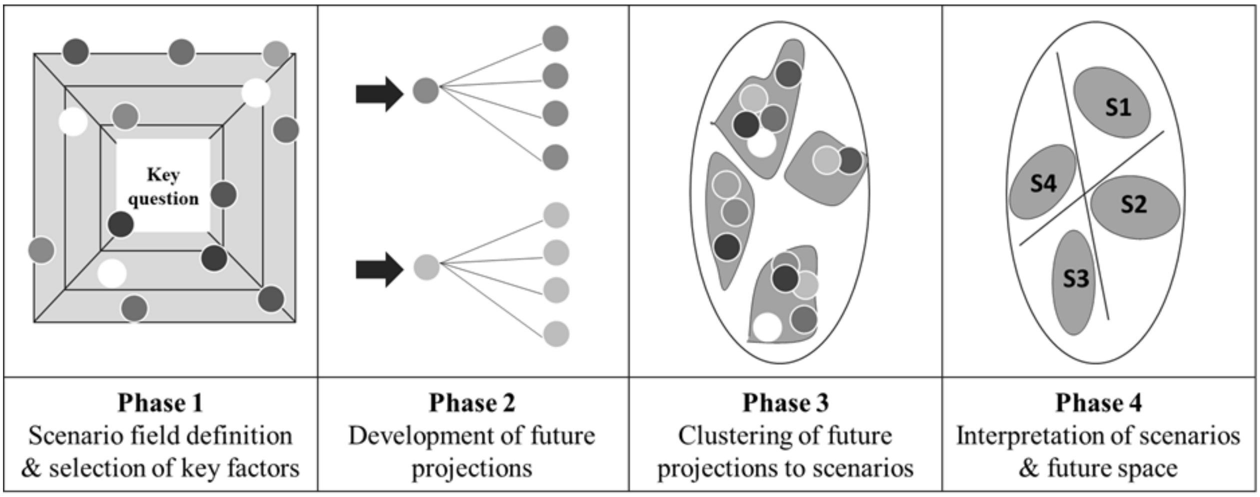


Figure 3.2: Phases of qualitative scenario management.
Source: Hoffart et al. (2020a).

In phase 1, the scenario field is defined. To do so, key aspects such as the topic area, the target group, the time horizon and the scenario objective are defined. Subsequently, the scenario field is structured and visualized in form of a system image and described by a large number of influence factors. These influence factors are identified in a brainstorming process based on the expertise of scenario team members. To reduce the number of influence factors to 15–25 key factors, an interconnection-relevance analysis is applied. The resulting key factors represent the driving forces of the scenario field and are the starting point for the scenario development.

During the second phase, future projections are identified for each key factor. These future projections describe possible future developments of one key factor, including extreme events.

In the third phase, highly consistent projections of the key factors are clustered to raw scenarios. A consistency analysis clusters all future projections to consistent projection bundles, which are reduced to 3–7 raw scenarios using a cluster analysis. Each raw scenario contains one future projection of each key factor.

In the fourth phase, the scenarios are analysed. Each scenario is first described in detail based on the list of future projections of each raw scenario. Second, the scenarios are interpreted referring to the following questions. Which scenario is desirable, which one is not? Comparing the scenarios, what are the main differences or similarities? What should be done today to realize a desirable scenario or prevent an undesirable scenario to materialize in the future

Table 3.1 and Table 3.2 describe the two parts of the macroeconomic approach in more detail. Table 3.1 shows the application of the qualitative scenario analysis to the German case study of

ELEGANCY. A core scenario team of three economic researchers worked through all process steps.

Table 3.1: Overview of the scenario analysis.

Step	*Task*	*Method*	*Result*	*Participation*
1	Scenario field definition	Interconnection-relevance analysis	System image, 52 influence factors, 23 key factors	Internal project workshop, discipline specific feedback
2	Development and combinations of future projections	Consistency analysis	100 future projections, projection bundles	Discipline specific feedback
3	Clustering of future projections	Cluster analysis, semi-structures discussions	6 raw scenarios	External stakeholder workshop
4	Scenario description and interpretation	Key factor-based story telling	6 story lines, 4 interaction level	non

Source: Author's own contribution.

In the first step, the scenario field was defined including the following key scenario questions: *What are alternative future developments of conditions that are relevant for a gas infrastructure modification for the year 2035 considering the German energy transition and sector coupling?* Political and private decision makers that are involved in the German gas sector and related sectors are selected as a target group. To grasp the complexity of energy system transformation, a system image was designed, which is shown in figure 3.3 and described later on. Based on a literature review and a brainstorming process, the core scenario team identified 111 influence factors. These influence factors were reduced to 52 influence factors and matched to all topic areas. By conducting an interconnection-relevance analysis, the 52 influence factors were again reduced in a more systematic way to 23 key factors.

To include the feedback from different disciplines and stakeholders, two feedback rounds were included in the process of scenario development. In a first feedback round, the German RUB case study team provided feedback for the conceptual work of phases 1 and 2. Including feedback from different disciplines and experts by using participatory methods is a core characteristic of the scenario analysis and the macroeconomic approach.

In the second step, the key factors are defined in more detail by developing future projections. For each key factor 4–5 future projections were developed by combining two dimensions. As a result, the 23 key factors exhibit a total 100 future projections. To gain a better understanding about the interdisciplinary characteristics of the projections, discipline-specific feedback was gathered. This exchange is crucial since the scenarios combine different perspectives and enrich the economic assessment with non-economic aspects. By conducting a consistency-analysis, the 100 future projections are clustered to highly consistent projection bundles, so-called raw scenarios.

In the third step, six raw scenarios are developed by using a cluster analysis. A raw scenario consists of 23 highly consistent future projections, to be more precise, one of each key factor. In a second feedback round, the raw scenarios were discussed with external stakeholder. For this purpose, regional energy experts were invited to participate in a stakeholder workshop. Their feedback was integrated into the description as well as the interpretation of the scenarios. Table 3.2 displays an overview of the participants of the stakeholder workshop.

Table 3.2: Overview of participants in feedback round 1 and 2.

Participant category	*Background*	*Number of scientists in feedback round 1*	*Number of scientists and business representatives, in feedback round 2*
Core scenario team	Economics	3	3
Case study team	Social sciences	2	2
	Law	2	-
	Engineering	2	1
Total internal participants		**9**	**5**
External participants		-	
	Scientific institutes		2
	Science		1
	Public company energy sector		1
	Private company gas sector		5
Total external participant			**9**
Total		**9**	**14**

Source: adapted from Hoffart et al. (2020a).

In the last step, the scenarios were described and interpreted. Based on the projections of the key factors, one detailed description for each scenario was developed (see section 3.2.2) These so-called story lines transmit the potential states of the German energy system and coupled sectors in the year 2035. To evaluate the degree of interaction and transformation of each scenario, the following 4 levels revealed to be crucial: level of conflict, level of stakeholder engagement, the overall level of transformation and the option of participation.

The developed six socio-technical qualitative scenarios (see section 3.2.2) constitute the framework for the evaluation of the ELEGANCY infrastructure options, which represents the second part of the macroeconomic approach (see Table 3.3)

To prepare for the scenario-based infrastructure evaluation, in the first step, the three infrastructure options were defined. To do so, the scenario core team conducted three discipline-specific workshops, one with each discipline. Three key requirements per discipline and infrastructure option were jointly identified. These key requirements describe discipline-specific requirements that need to be fulfilled to realize the respective infrastructure option. Including the macroeconomic key requirements defined by the core scenario team resulted in a total of 36 key requirements.

In the second step, to specify the key requirements, the scenario core team used the 23 key factors identified in part 1. For each key requirement, 1-3 key factors are identified which best represent the respective key requirement. This step can be understood as translation of the infrastructure options into the language of the scenario development. By assigning the key factors to the key requirements, the infrastructure options can be evaluated in terms of consistency with the different scenarios.

In a third step, the feasibility of the infrastructure options was evaluated using a consistency analysis. The six socio-technical scenarios function as a framework to assess whether the fulfilment of the key requirement is consistent with a certain scenario. This consistency-analysis results in 216 consistency values, meaning one consistency value per key requirement and scenario, which was applied to all six scenarios and to the three infrastructure options.

Table 3.3: Overview of the scenario-based infrastructure evaluation.

Step	*Task*	*Method*	*Result*	*Participation*

1	Definition of infrastructure options	Definition of 3 key requirements per infrastructure option and discipline	36 key requirements	3 discipline specific workshops & feedback
2	Specification of infrastructure options	Identification of 1-3 related key factors per key requirement	1-3 key factors per key requirement	Scenario core team
3	Evaluation of infrastructure feasibility	Consistency analysis	216 consistency values	Scenario core team
4	Assessment of key requirements	Assessment of realization and costs	5 critical key requirements	Discipline specific feedback
5	Calculation of consistency scores, interpretation of key requirements	Interdisciplinary infrastructure evaluation Stakeholder analysis	12 discipline-specific consistency levels, 4 option-specific consistency levels, 18 scenario-specific consistency levels	Scenario core team

Source: Author's own contribution.

In a fourth step, the key requirements were assessed independently from the scenario context. To identify the most critical key requirements, each discipline assessed the chance of realization and the related costs for the fulfilment of the discipline-specific key requirement. As a result, 15 critical key requirements, both supporting and hindering were identified (see 3.3.1)

As a final step, different aggregated consistency scores were calculated resulting in 12 discipline-specific consistency levels, 3 option-specific consistency levels and 18 scenario-specific consistency levels. The different consistency levels were used for the final interdisciplinary assessment of the three infrastructure options. To complete the scenario and stakeholder analysis, the relevant stakeholder for the fulfilment of each key requirement were identified using the 5 stakeholder groups (see. 3.3.2).

3.2 Part 1: Scenario analysis

3.2.1 Scenario development

In the following, different steps of the scenario development process and related results are described in more detail. More details on the scenario development as well as the value added of the method compared to a traditional approach can be found in Hoffart et al. [HOF20a].

During the first phase of the scenario development, a structured system image was developed that visualizes the scenario field and is arranged in system levels and topic areas. Following McInerny et al. [MCI14], a visualized system image was applied to capture the complexity of the German energy system. By designing the system image, the complex interrelation among the system levels and topic areas were captured, as displayed in Figure 3.3. The creation of the system image was challenging for two reasons. On the one hand, relevant sectors and actors of the German gas sector needed to be identified. Their interconnection, background conditions and interests needed to be detected as well. On the other hand, by visualizing these aspects systemically, the hierarchical structure of the system needed to be displayed properly.

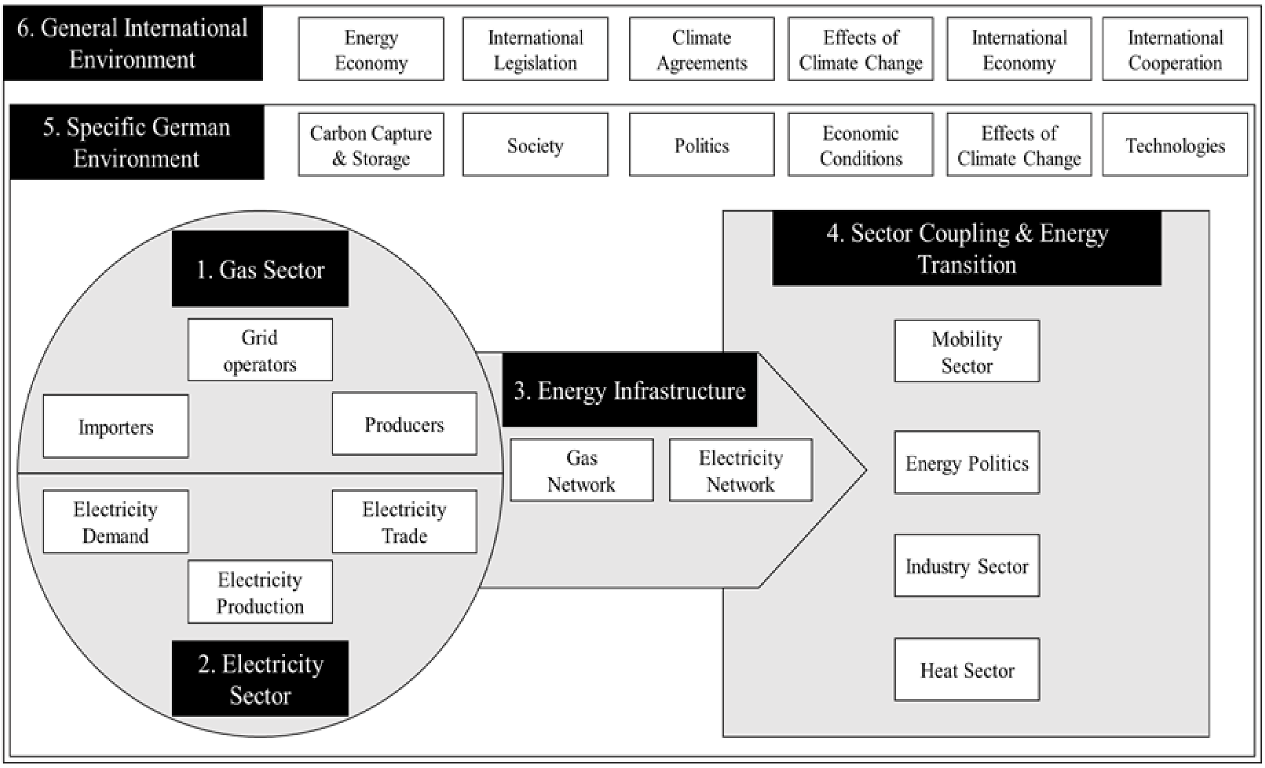


Figure 3.3: System image.
Source: Hoffart et al. (2020a).

The first and second system levels represent the energy sector, which comprises – in the scope of this analysis – the gas and the electricity sector, that can hardly be considered separately. The central position of the energy sector underlines the importance of the energy sector as the pivotal point of the analysis. Both sectors are regarded as highly interlinked. They are characterized by topic areas such as producers (gas sector) or electricity production (electricity sector). The gas and electricity sector represent the supply side of the energy system and are connected to the consumer side via the energy infrastructure. The energy infrastructure is represented by system level 3 and contains the gas and the electricity network. System level 4 represents the demand side and brings together the coupled sectors such as the industry, mobility and heating sectors. This system level also includes energy politics, as it mainly shapes the energy transition and thus the development of the supply and demand side. These four system levels form the core area of the scenario field and are embedded in the specific German environment (system level 5) and the general international environment (system level 6). These two rather general system levels represent the framework conditions that shape the development of the core area, such as economic conditions, diffusion of technologies, effects of climate change or international legislation. The goal of creating such a system image is to broaden the perspective of the analysis and to explicitly include societal, legal and technical aspects into the macroeconomic analysis framework.

As the approach's understanding of feasibility implies, identifying and addressing possible hurdles is crucial for a successful implementation of infrastructure modification. Qualitative scenario development helps to understand what factors foster or hinder a successful implementation by identifying key factors relevant for the low-carbon transition. These factors cover all systems level, include also non-economic and non-technical focus, and thus exceed the traditional techno-economic focus.

Applying an interconnection-relevance analysis, 23 key factors were identified. Each influence factor was evaluated in terms of its activity and its passivity and is visualized in an active-passive grid. While the activity score determines to what extent a factor influences other factors, the passivity score determines to what extent the factor is influenced by other factors. In the active-passive grid, the influence factors are classified in the four categories, namely independent factors, indicators, system nodes and levers (see Figure 3.4).

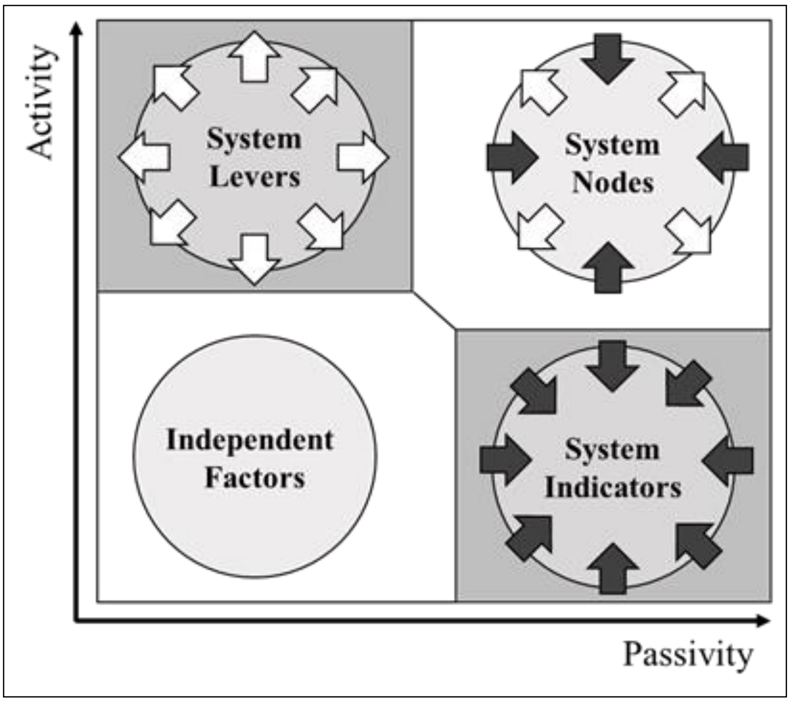


Figure 3.4: System relevance analysis.
Source: Hoffart et al. (2020a).

Independent factors have a low interconnection to the whole system, both in terms of activity and passivity. Due to their marginal effect on the systems dynamic, independent factors can be neglected. System indicators have a low influence on the whole system (low activity) but are highly influenced be other factors (high passivity). To be more precise, these factors indicate changes of the whole system. System levers have a high influence on the whole system (high activity) with hardly any feedback effects (low passivity). Changes related to these factors influence the system’s dynamic in many ways. System nodes are highly connected to the whole system, both in activity and passivity terms. Changes of these factors result in complex reciprocal effects and should therefore be included as key factor.

Table 3.4 lists the 23 key factors, which were grouped in six categories to understand main drivers. Against the initial intuition technological progress revealed to be no key factor, but as a system indicator. This result is in line with the understanding of feasibility considering technological feasibility as a necessary precondition that is less relevant for the implements itself. That measure, such as the *Phase Out & Phase In: Fossil & Renew.(#2), cost of carbon (#4) or lignite energy phase out (#17)* form an own category demonstrated the potential high influence of the government.

Table 3.4: Key factors.

Categories	*Key Factors*
Outcomes	#1 Realization of National Climate Goals
Stakeholders	#21 Investors in Gas-Related Technologies
	#22 Character of Public Policy
	#15 Power of Lobbyism
	#8 Influence of Public Interest Groups
	#7 Behaviour & Public Acceptance
Measures	#2 Phase Out & Phase In: Fossil & Renew. Gas
	#4 Cost of Carbon
	#12 Carbon Capture Technologies
	#17 Lignite Energy Phase Out
	#23 Governmental Support for Transformation Technologies
Sector-specific Developments	#9 Fuel of Road Traffic
	#18 Heating
	#11German Production of H_2
	#19 H_2 Power Plants
	#20 Technological Progress & Market Maturity
Infrastructure Developments	#5 Electricity Network Expansion
	#14 Gas Network Expansion
Energy-related Developments	#6 Electricity Production
	#10 German Gas Demand
	#16 Import of H_2
	#13 Electricity Consumer Price
	#3 Natural Gas Price

Source: based on Hoffart et al. (2020a).

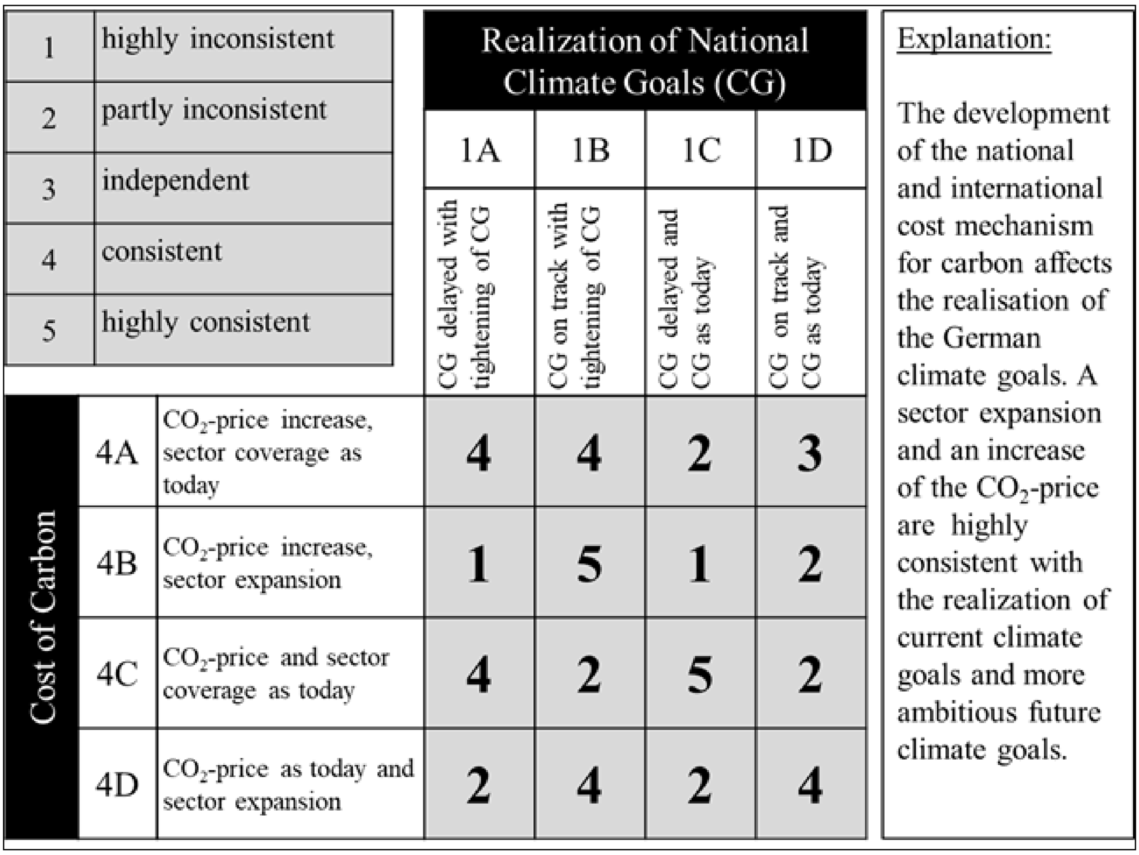
The key factor lists also show the importance of stakeholders. Stakeholders represent an own category and comprise 5 key factors which refer to the following stakeholder groups (see Table 3.5): (1) political decision-makers, (2) citizens & society, (3) public interest groups, (4) economic lobby groups, (5) investors in gas sectors (see Table 3.5).

Table 3.5: Key factor-based stakeholder groups.

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

Source: based on Hoffart et al. (2020a).

In the next phase, the key factors were defined in more detail by developing future projections. These future projections show possible pathways of future development that are relevant for the scenario objective. For each key factor 4-5 future projection were developed by combining two dimensions. Contrary to traditional techno-economic studies, the high level of uncertainty is incorporated by explicitly allowing for different pathways of future developments. Figure 3.5 shows possible pathways of two key factors, namely *Realization of National Climate Goals* (#1) with the future projections 1A-1D and *Cost of carbon (#4)* and respectively 4A-4D. Figure 3.5 also shows exemplarily one part of the consistency analysis applied in the next step to combine projections bundles according to their logical consistency to raw scenarios. For this purpose, a consistency matrix is used to analyse the relation between the future projections (relation rating: highly consistent, consistent, independent/neutral, partially inconsistent, totally inconsistent). The consistency analysis and the subsequent cluster analysis are again methods to deal with the high level of complexity in a systematic, analytical way.



1	highly inconsistent
2	partly inconsistent
3	independent
4	consistent
5	highly consistent

			Realization of National Climate Goals (CG)			
			1A	1B	1C	1D
			CG delayed with tightening of CG	CG on track with tightening of CG	CG delayed and CG as today	CG on track and CG as today
Cost of Carbon	4A	CO_2-price increase, sector coverage as today	4	4	2	3
	4B	CO_2-price increase, sector expansion	1	5	1	2
	4C	CO_2-price and sector coverage as today	4	2	5	2
	4D	CO_2-price as today and sector expansion	2	4	2	4

Explanation:

The development of the national and international cost mechanism for carbon affects the realisation of the German climate goals. A sector expansion and an increase of the CO_2-price are highly consistent with the realization of current climate goals and more ambitious future climate goals.

Figure 3.5: The consistency matrix..
Source: Hoffart et al. (2020a).

3.2.2 Scenario description and interpretation

The qualitative scenario development results in six qualitative socio-technical scenarios, that are displayed in Table 3.6. These scenarios were characterized in terms of the level of transformation, the level of engagement, the level of conflict and the option for participation.

Table 3.6: The socio-technical ELEGANCY scenarios.

Socio-technical scenarios	***Level of transformation***	***Level of engagement***	***Level of conflict***	***Option for participation***
(1) Fossil revival instead of green progress	1	1	1	1
(2) Technology-open green transformation	3	3	2	3
(3) Green transformation with hydrogen	3	3	1	3
(4) Incremental green transformation	2	2	1	2
(5) Top-down effort & conflicting interests	2	3	3	3
(6) Bottom-up effort & political inaction	2	2	2	1

1 = low, 2= medium, 3= high

Source: based on Hoffart et al. (2020a).

In the following, the six scenarios are described in more detail before being interpreted afterwards.

Scenario 1: Fossil revival instead of green progress

Scenario 1 is characterized by a fossil revival as opposed to progress in terms of sustainable development. Compared to a BAU scenario, scenario 1 represents a worsening of the status quo. Throughout all stakeholder groups, there is hardly any commitment for a transformation towards a low-carbon economy and society (level of engagement = 1). In contrast to the last years' effort to increase the share of renewable energy, there is a broad consensus to focus again on fossil resources and energy. Hence, the overall level of green transformation is very low (level of transformation = 1). Amongst the stakeholder groups, there is no significant conflict of interests about the course for the future (level of conflict = 1).

This consensus about the fossil redirection of the German energy system is also reflected by the character of public policy. While there are more governmental resources available to foster a green transformation, there is no political will to do so (#22: Character of Public Policy). The high financial resources are due to the strong cut of the budget for the energy transformation and restrictive handling of the national budget. Governmental support for hydrogen technologies and the electrification are missing. (#23: Governmental Support for Transformation Technologies). Plans for a phase out of fossil gases or a phase in of renewable gas do not exist, which would be the next step after the decision to phase out coal energy (#2: Phase Out & Phase In: Fossil & Renew. Gas). Similarly, the lignite energy phase, which was started in 2019, is not finished but delayed. (#17: Lignite Energy Phase Out). The delay is also due to the strong influence of the dominating fossil lobby groups and conservative anti-transformation interest groups (#15: Power of Lobbyism; #8: Influence of Public Interest Groups). This anti-transformation attitude is also observable in society, as the acceptance of new technologies is low. (#7: Behaviour & Public Acceptance). In general, last years' political decisions towards the energy transformation did not find support from the society. Protests against the national electricity network expansion caused a massive delay and high unexpected costs (#5: Electricity Network Expansion). Due to the anti-transformation attitude and the general rejection of transformational technologies, carbon capture technologies and related transport and storage are not feasible on a national and international scale (#12: Carbon Capture Technologies). Concerning the market maturity and technological progress of hydrogen and battery technologies, there is no significant progress necessary to incentivize a breakthrough of renewable technologies in several sectors (#20: Technological Progress & Market Maturity). As a result of the fossil revival, natural gas still dominates the heating sector. Hydrogen- and electro technologies are hardly used for heating purposes. (#18: Heating) A similar picture can be drawn for the mobility sector. Fossil fuels still represent the dominating energy source, whereas hydrogen and electricity play no important role (#9: Fuel of Road Traffic). Consequently, the total demand of gas increases, while demand for renewable gas is negligible (#10: German Gas Demand). Even though the gas price rose, it is still cheaper than hydrogen (#3: Price Natural Gas), which reflects the global stagnation towards an energy system transformation. Political decisions mainly affected the share of renewable energies, whereas privileges for renewable are abandoned (#13: Electricity Consumer Price). After introducing a German carbon pricing system in 2020, neither the price nor the sector coverage increased. (#4: Cost of Carbon). The decreasing production of renewable energy is displayed in the German energy mix, which is characterized by a relatively low share of renewable energy. Since the fossil revival stopped the expected electrification, the general volume of electricity production did not increase rapidly (#6: Electricity Production). Due to the low amount of surplus energy, initial plans for large-scale power-to-x hydrogen production were not implemented. (#11: German Production of H_2). Also, hydrogen power plants play no role for the electricity production in Germany as it was expected in 2019. (#19: H_2 Power Plants). Due to the high price of hydrogen and resulting low demand, there is no need to modify the gas grid. Therefore, no plans exist for adapting the gas infrastructure to hydrogen (#14: Gas Network expansion). To satisfy the industry’s demand for hydrogen, mainly grey H_2 is imported. (#16: Import of H_2). Due to missing business opportunities and demand of H_2, there are no incentives to invest in hydrogen application and related infrastructure (#21: Investors in Gas-Related Technologies).

In this scenario, renewable energies and especially hydrogen play no important role for the Germany energy system. The last years’ progress of fostering renewable energy was outweighed by a reorientation towards fossil fuels and energy and budget cuts. The mobility and heating sector still heavily rely on fossil fuels. As a result, the fulfilment of the national climate goals is delayed (#1: Realization of national Climate Goals).

Scenario 2: Technology-open green transformation

Scenario 2 is characterized by a very high level of green transformation (level of transformation = 3). The positive development in terms of sustainability is due to a strong commitment of all stakeholder groups (level of engagement = 3) and a broad consensus (level of conflict = 2) to foster the transformation towards a low-carbon economy and society.

The supportive strong public discourse is dominated by public interest groups fostering the low-carbon transformation and a public curiosity for new technologies (#8: Influence of Public Interest Groups). Such an openness related to both hydrogen- and e-applications represents a key characteristic of scenario 2 (#7: Behaviour & Public Acceptance). Consequently, political decisions to promote the green transformation are widely accepted and supported among the population. In this societal setting, the government successfully initiates several transformation fostering policies (#22: Character of Public Policy). As a cross-sectoral political decision, the German government expands the carbon price mechanism on further sectors and simultaneously increases the carbon price (#4: Cost of Carbon). The critical topic of CCS gained supporters, which increases the national and international feasibility of CCS technologies and infrastructure (#12: Carbon Capture Technologies). These developments created substantial incentives and planning security for the economy and supports the public request for climate mitigation measures and a related energy system transformation. The decision to phase out lignite-based energy was successfully translated into practice in a structured way and is nearly completed (#17: Lignite Energy Phase Out). To further decarbonize the energy sector, the German government announced detailed plans to phase out fossil gas and introduced a quote for renewable gases (#2: Phase Out & Phase In: Fossil & Renew. Gas). These plans are a progressive step towards a carbon-free economy. Due to the pro-transformation attitude of the government and the general public, a power shift among the economy took place. The influence of fossil lobby groups significantly decreased (#15: Power of Lobbyism), while transformative lobby groups gained in importance and influence. Political support for low-carbon technologies and the unified interest of economy and society to transform the economy results in a good climate for investment in gas-related technologies and infrastructure (#21: Investors in Gas-Related Technologies). Research and development of hydrogen applications as well as storage technologies for renewable energies are strongly financed by private investors and governmental support programs (#23: Governmental Support for Transformation Technologies). Such massive investments result in marketable products (#20: Technological Progress & Market Maturity). Especially, the mobility and heating sector benefit from the progressive development of hydrogen and electro technologies (#18: Heating). As a consequence, fossil fuels are neglectable whereas hydrogen and electro-technologies play the dominating role (#9: Fuel of Road Traffic). Such innovations are broadly accepted by the general public even though the electricity price increases (#13: Electricity Consumer Price). In line with the privileged status of hydrogen- and electro technologies, the share of renewable electricity in the German energy mix increases (#6: Electricity Production). With the broad entrance of e-application in the sectors of heating and mobility, the electricity production increases as well. The ongoing electrification demands a fast realization of the national electricity network expansion, causing high unexpected costs (#5: Electricity Network Expansion). A strong increase of hydrogen in the energy sector has a twofold effect. First, based on the increased carbon price, hydrogen becomes relatively cheaper than natural gas (#3: Natural Gas Price). The new importance of hydrogen as an energy carrier in the mobility sector and in the heating sector increases the demand for gas in general and green hydrogen in particular. (#10: German Gas Demand) The production and import of green H_2 increases strongly (#16: Import of H_2) (#11: German Production of H_2). Second, plans for an extensive regional gas network modification to adapt to hydrogen are announced and mark the cornerstone for a hydrogen infrastructure (#14: Gas Network. Expansion)

The progressive engagement of the government to transform the Germany energy system is supported by the general public. The introduced policies incentivize the German economy to introduce hydrogen through all sectors. The technology-open government subsidies allow both electro and hydrogen technologies to foster (#23: Government Support for Transformation Technologies). These developments secure the fulfilment of the national climate goals. The progressive societal atmosphere sets the cornerstone for the government to tighten the national climate goals for the next decades (#1: Realization of national Climate Goals).

Scenario 3: Green transformation with hydrogen

Scenario 3 describes a progressive future of Germany, where the low-carbon transformation of Germany and the energy sector enjoy a high priority (Level of Transformation = 3). All stakeholder groups, including political decision makers, the general public and economic actors, engage in the transformation (Level of Engagement = 3). Notable conflicts about the future direction of Germany in terms of climate change mitigation do now exist (Level of conflict = 1).

Such a low level of conflict has several reasons. At the political level, decision makers show a high intent to support the transformation and provide financial means (#22: Character of Public Policy). Simultaneously, the need to tackle climate change facilitates the influence of public interest groups (#8: Influence Public Interest Groups). Such shifts amplify the curiosity for renewable technologies among the society and foster transformation-supporting political decisions (#7: Behaviour & Public Acceptance).

The German government had decided the phase out of lignite energy in the year 2019. In 2035, the lignite energy phase out is almost completed although rather unstructured (#17: Lignite Energy Phase Out). At the same time, the government decided to increase the carbon price and to include further sectors, which set a strong signal against the use of fossil fuels and energy (#4: Cost of Carbon). To emphasize the transformation from fossil-based energies to renewable, carbon-free alternatives, the government presents plans for the phase out of natural gas and a future mandatory phase of renewable gases (#2: Phase Out & Phase In: Fossil & Renew. Gas). Plans for a nationwide extensive modification of the German gas infrastructure are presented (#14: Gas Network Expansion). The feasibility of CCS technologies as a bridging technology to achieve a carbon-free energy system is given. Due to bilateral negotiations between the Netherlands and Germany, CO_2 can now be exported for offshore CCS in the Netherlands. (#12: Carbon Capture Technologies). These developments influence the market and change the importance of hydrogen compared to natural gas. Hydrogen is now cheaper than natural gas (#3: Natural Gas Price). Such a setting enables a profitable implementation of hydrogen power stations (#19: H_2 Power Plants) and results in strong increase of renewable energy in the German electricity mix (#6: Electricity Production). These policies foster the use of hydrogen increasing the demand for gas in general and renewable gases in particular. (#10: German Gas Demand). To satisfy the demand for renewable gases, the German production of green hydrogen (#11: German Production of H2) as well as H_2 imports increased (#16: Import of H_2). The government's strong support for hydrogen affects the society and economy.

The public pro-transformation interest groups gain influence, whereas conservative and fossil lobby groups lose power (#15: Power of Lobbyism). In addition to the strong incentives set by the government, this power shift stimulates investments in gas-related green technologies (#21: Investors in Gas-Related Technologies). Consequently, the mobility and heating sector shift from carbon-based to renewable energy sources, which is amplified by governmental subsidies for hydrogen (#23: Governmental Support for Transformation Technologies). This leads to higher market shares of hydrogen technologies outweighing electro-technologies (#20: Technological Progress & Market Maturity). The strong focus on hydrogen and other renewable gases leads to a relative high share of hydrogen applications in mobility and heating sector. (#18: Heating) (#9: Fuel of Road Traffic). While renewable technologies enjoy a privileged electricity price, the energy price increased (#13: Electricity Consumer Price). The electricity network expansion is slightly delayed causing moderate additional costs (#5: Electricity Network Expansion).

In a nutshell, scenario 3 shows a high level of transformation with a dominating role of hydrogen. Such progressive steps lead to the realization of the national climate goals and indicate more ambitious future climate goals (#1: Realization of National Climate Goals).

Scenario 4: Incremental green transformation

In scenario 4, all stakeholder groups agree on the need to transform the economy and society towards a low-carbon future (level of engagement = 2). The general level of ambition is, however, rather low, although the political intent to foster the transformation is high (#22: Character of Public Policy). The government decided to achieve the low-carbon future with small, incremental steps (level of transformation = 2). The guiding principle remains 'economy first, transformation second'. Thus, economic efficiency and stability of economic welfare dominate the discussion about the low-carbon transformation (level of conflict = 1). In line with this principle, the lignite coal phase out proceeds in a structured manner but is still not finished (#17: Lignite Energy Phase out). As a positive sign, the share of renewables increases strongly (#6: Electricity Production), which is fuelled by the privileged status of renewables in the electricity production. The electricity price slightly increases, (#13: Electricity Consumer Price) whereas the high share of renewable energy expands the need for an electricity network expansion to ensure a stable electricity supply. Despite this need, the expansion of the electricity network is delayed causing moderate additional costs. (#5: Electricity Network Expansion),

To meet the national climate goals, the government concentrates on three areas: pricing of CO_2, carbon-capture technologies, and phase in of renewable gas. Nevertheless, extensive subsidies for specific technologies such as hydrogen or electrification technologies or application, is not planned by the government (#23: Governmental Support for Transformation Technologies). This hesitant decision can be explained by a relatively weak lobby for hydrogen and electrification, such that the interests of the transformative lobbies are not sufficiently advocated (#15: Power of Lobbyism). As a step towards the low-carbon transition, the government extends the sector coverage of CO_2 pricing mechanisms to achieve large scale effects and incentivize the economy. But, to prevent disruptive effects for the economy, the price for CO_2-emissions is not raised (#4: Cost of Carbon). To achieve the national climate goals, carbon-capture technologies are implemented on a national scale (#12: Carbon Capture Technologies). The public acknowledges the CO_2 saving potential of CCS, which outweighs the general scepticism against the technology. In line with the political support for renewable electricity production, the government announced plans to phase in renewable gases. A phase out of fossil gases was postponed. To phase in renewable gases, two options are heavily discussed: a quota for renewable gases in the German gas mix and a guaranteed minimum price for hydrogen producers (#2: Phase Out & Phase In: Fossil & Renew. Gas). These political decisions are endorsed by the public, who appreciates the level of effort, but remains sceptical towards new technologies (#7: Behaviour & Public Acceptance). Both conservative and pro-transformation public interest groups are visible, but are not very active, which explains their rather low influence on the public discourse (#8: Influence of Public Interest Groups). The principle 'economy first, transformation second' also lead to two unwanted developments: firstly, it prevents the emergence of a powerful transformative lobby and conserves the dominant position of fossil lobby groups. Secondly, it does not allow for the required technological process of transformational technologies such as hydrogen and energy storage technologies (#20: Technological Progress & Market Maturity). At the same time, consumers are sceptical about these new technologies. Consequently, the use of hydrogen and electricity as a fuel of road traffic and as a source for heating increases only slightly. In both sectors, fossil fuels still dominate the supply of energy, while the share of low-carbon fuels incrementally increases (#18: Heating; #9: Fuel of Road Traffic). This leads to an increase in German demand of natural gas, whereas the share of imported renewable gas is relatively low (#10: German Gas Demand). The price for natural gas increases and meets the same level as hydrogen (#3: Natural Gas Price). The plans to phase in renewable gas raises the attention of investors, who increasingly plan to invest in gas-related technologies (#21: Investors in Gas-Related Technologies). The level of investments remains relatively low. As a result, first pilot power plants producing energy from hydrogen are installed and operate profitably (#19: H_2 Power Plants). Plans to adjust the gas network to hydrogen on a regional level are put into practice. (#14: Gas Network Expansion), leading to a moderate increase in blue hydrogen imports. (#16: Import of H_2). The national production of hydrogen remains on a small level (#11: German Production of H_2).

Hydrogen slowly increases in importance, such that an economically feasible hydrogen market is possible. The small and efficient steps towards a low-carbon future might be enough to realize the current climate goals. Plans to tighten the climate goals do not exist. (#1: Realization of national climate goals).

Scenario 5: Top-down effort & conflicting interests

In scenario 5, the stakeholder groups are very influential, but have conflicting interests. Government, society, public interest groups and lobby groups are facing the challenge to agree on a common vision for a low-carbon future and find a compromise concerning their different interests. Thus, the level of conflict is high (Level of conflict = 3) meaning that the time-intensive process of finding a consensus consumes a lot of resources. Due to the high transaction costs, decision-making and the resulting action are slowed down (Level of transformation = 2). The atmosphere of ambitious players mobilizes various parts of the general public to actively engage in the process of transformation (level of engagement = 3).

The government has a high intention to strive for a low-carbon transformation and invests a significant amount of resources to accelerate the transformation (#22: Character of Public Policy). Due to the government's high ambitions, the national climate goal got intensified (#1: Realization of National Climate Goals). This tightening of the national climate goals is accompanied by an expansion of the sector coverage of the carbon price. The carbon price remains the same (#4: Cost of Carbon). At the same time, the government offers extensive financial support for both hydrogen und electro-technologies in order to push transformation technologies (#23: Governmental Support for Transformation Technologies). The new climate goals seem to be too ambitious, since the strong fossil lobby is dominating the economic discourse and counteracts the transformation (#15: Power of Lobbyism). Public interest groups also have a strong influence but are split into a pro-transformation and a conservative camp (#8: Influence of Public Interest Groups). The pro-transformation groups follow a different agenda than the government, since a common vision for the low-carbon transformation is missing. The ambivalence concerning the transformation is displayed in society, too. While the majority of the population is open for new technologies, there is a general mistrust concerning the government's decisions (#7: Behaviour & Public Acceptance). Although the population is in favor of a transformation, the majority is dissatisfied with the time-consuming process of consensus building. They criticize the process as being counterproductive and inefficient. While there was a consensus for an incremental phasing out of lignite energy, there is large disagreement on how the process should be realized. Consequently, the lignite energy phase out is still delayed (#17: Lignite Energy Phase Out). As a next step towards a low-carbon economy, the government aims to phase in renewable gas. After successful, but long, negotiations, the government reached a consensus on how to phase in renewable gas. The phase out of fossil gases is postponed due to massive protests from the fossil lobby (#2: Phase Out & Phase In: Fossil & Renew. Gas). Despite the extensive governmental support for transformation technologies for heating and mobility (#23: Governmental Support for Transformation Technologies), the privileged electricity price for renewable technologies (#13: Electricity Consumer Price), as well as the expected breakthrough concerning electric and hydrogen technologies did not materialize. Although the price for hydrogen is cheaper than for natural gas (#3: Price Natural Gas), the usage of hydrogen and electro technologies for heating and mobility did increase only slightly. Fossil fuels remain the dominant energy resource in both sectors (#18: Heating; #9: Fuel of Road Traffic). These developments are fuelled by the missing of technological progress in hydrogen application and storage technologies (#20: Technological Progress & Market Maturity). Due to the extensive use of natural gas, the demand for its import increases significantly (#10: German Gas Demand). In the same vein, the demand for renewable gases experienced a small increase. Recently, hydrogen power plants were installed for research purposes and are far away from being profitable (#19: H_2 Power Plants). The relatively small demand for hydrogen is covered by import of green H_2 (#16: Import of H_2), which is why the German H_2 production remains negligible (#11:

German Production of H_2). After a long discussion on the future of hydrogen and a related infrastructure, the parties agreed on a nationwide, but marginal, modification of the gas network to adjust to hydrogen. This consensus represents a compromise between the strong transformative public interest groups on the one side and the conservative fossil lobby at the other side (#14: Gas Network Expansion). As an attempt to reduce German carbon emissions, international agreements for carbon capture and storage technologies were contracted (#12: Carbon Capture Technologies). These developments in the gas sector attract investors. Investments in the gas infrastructure for natural gas, hydrogen and carbon dioxide increase moderately. Similarly, investments for hydrogen technologies exhibit a strong increase (#21: Investors in Gas-Related Technologies).

The powerful fossil lobby influences the development related to the expansion of renewable energy. As a consequence, the share of renewables did not increase as significantly as it was initially planned (#6: Electricity Production). Another reason for this development is the strongly delayed expansion of the electricity network. The realization of the national expansion plan caused high exceptional costs due to protest and disagreement between the involved stakeholders (#5: Electricity Network Expansion).

In sum, the government shows a high intent to foster the low-carbon transformation and tightens the climate goals. The conflict between the involved stakeholder groups, however, impedes the realization of existing climate goals (#1: Realization of National Climate Goals).

Scenario 6: Bottom-up effort & political inaction

Scenario 6 is characterized by a strong bottom-up movement to accelerate a low-carbon transformation. Public interest group and the lobby groups both strongly support the transformation (#8 Influence of Public Interest Groups). Societal stakeholder groups show a great commitment and engagement in fostering the public discussion on transformation-supporting means (Level of engagement = 2). The general public shows a high acceptance for new transformation technologies and actively calls for more progressive policies (#7: Behaviour & Public Acceptance). Consequently, the influence of conservative public interest groups declines, which boots the power of transformation-oriented interest group (#8: Influence of Public Interest Groups). At the same time, economic stakeholders request a severe shift in the energy system and call for serious, transformational attempts. The broad commitment for a low-carbon transformation decreases the influence of the fossil lobby groups. It also allows the pro-transformation lobby, which aims to foster hydrogen and electrification, to gain in importance (#15: Power of Lobbyism). The commitment of the society and economy is confronted (Level of conflict = 2) with a low political intent and low financial resources (#22: Character of Public Policy). Due to the low prioritization of climate change mitigation, transformation-fostering policies are missing and plans to transform the energy system are postponed. The CO_2 price remains the same as well as the sector coverage, which is not extended (#4: Cost of Carbon). Similarly, a heavily discussed phase in of renewable gases and the related phase-out of fossil gases is postponed (#2: Phase Out & Phase In: Fossil & Renew. Gas). The governmental inaction concerning the low-carbon transformation also has a negative impact on the feasibility of carbon capture technologies. Required negotiations with neighbouring countries are postponed, although the scepticism of the German public declined (#12: Carbon Capture Technologies). National long-term projects, such as the expansion of the electricity network or the phase out of lignite coal, are behind the schedule (#5: Electricity Network Expansion) (#17: Lignite Energy Phase Out). The price of electricity decreases. (#13: Electricity Consumer Price). Without guiding policies, the German government misses the opportunity to provide planning security for the economy. Such a reticent behaviour leads to mixed results in the transformational progress and hinders the success of the high level of engagement (Level of transformation = 2). As a positive sign, the investment interest in gas-related technologies and infrastructure increases. (#21: Investors in Gas-Related

Technologies). Simultaneously, the developments in the gas sector market increase the profitability of investments. This change is indicated by a harmonization of the natural gas price and the price for hydrogen (#3: Natural Gas Price). Consequently, there is technical progress in developing transformational technologies for hydrogen applications and storage devices (#20: Technological Progress & Market Maturity). Especially the exploration of and the investment in hydrogen power plants bears fruits. The first hydrogen power plant project, which started for research purposes, runs profitably (#19: H_2 Power Plants). Such successes motivate private investors for a regional modification of the national gas network with the goal to develop a hydrogen-compatible network (#14: Gas Network Expansion). These efforts affect the demand and production of hydrogen. An increased demand for hydrogen and the availability of private funding increase the German production of green hydrogen (#11: German Production of H_2). To satisfy the new demand for renewable gases (#10: German Gas Demand), imports of blue H_2 increase strongly. (#16: Import of H_2). The electrolysis based H_2 production fosters the volume and share of renewables electricity (#6: Electricity Production). Besides these positive developments, the breakthrough of hydrogen and electricity technologies is missing, as subsidies for these technologies are missing as well. (#23: Governmental Support for Transformation Technologies). Thus, the moderate share of alternative fuels is based on the engagement of individual pioneers, not on governmental engagement. In the heating and mobility sector, the use of hydrogen, while electrification application is still behind expectations (#9: Fuel of Road Traffic) (#18: Heating).

The German government fails in providing a comprehensive framework for the low-carbon transformation and thus hinders the transformation, which is what all stakeholder groups call for. Therefore, Germany is not able to keep on track with its national climate goals (#1: Realization of National Climate Goals).

The scenarios can be interpreted in different ways. Although all scenarios are in general possible and developed explicitly without assigning probabilities, it is useful to interpret them in term of their desirability and probability in a next step. Since scenario 2 and scenario 3 show the highest level of low-carbon transformation and thus the highest chance to successfully implement an H_2/CCS infrastructure, they can be interpreted as the best-case scenario. Scenario 1 represents, as the name *fossil revival instead of green progress* describes, a negative development. Since a worsening of the current status quo took place in the form of the whole society jointly abandoning to strive for sustainability, it represents the worst-case scenario. Scenario 4, scenario 5 and scenario 6 show positive as well as negative developments concerning different aspects and levels. A detailed analysis of what scenario is the most and the least desirable and realistic one, exceeds the scope of the project. It is, however, crucial to develop an understanding of common patterns between all scenarios. Independently from what scenario, and thus future, will materialize in the end, these patterns provide the foundation for future robust policies and decisions. From a systems perspective, three key messages can be formulated and cover common patters.

First, there is not one most important key factor that determines the feasibility of a H_2/CCS infrastructure in Germany. Nevertheless, stakeholder dynamics play a major role for a successful infrastructure implementation. The availability of technologies and technological progress, however, plays a minor role, which is in line with the approaches' understanding of feasibility (see Figure 3.1). It does not mean that technical aspects are not important. Instead, technical feasibility is a necessary precondition. When it comes to the implementation, technical feasibility was already assessed. Whether or not a certain technology is in the end implemented and used depends on other factors, such as the public acceptance or subsidies for low-carbon technologies. To modify the gas infrastructure, the broader context, the legal framework and long-term planning were identified as crucial factors.

Second, the overall level of transformation was revealed to be most important, as it mainly determines the feasibility of the case study's different infrastructure options. To be more precise, the further a country's low-carbon transformation has progressed, the more feasible it is to implement extensive infrastructure modifications. The building of new pipelines or a completely new infrastructure, such as it is aimed at in the infrastructure options 1 and infrastructure option 3, would be a more extensive modification compared to infrastructure option 2. The overall level of transformation is mainly determined by stakeholder dynamics, which define the scenarios' setting. The differences in the overall level of transformation between the scenarios can be explained by varying stakeholder dynamics. These dynamics are displayed by different levels of conflict and engagement and the option for participation.

It implies, third, that the commitment of all stakeholder groups is required. On the one hand, it means that the bottom-up commitment of the society and economy is not sufficient to foster a high level of overall low-carbon transformation, as long as political will is missing as the example of scenario 6 showed. On the other, political intent and related decisions are necessary, but not sufficient for a high level of low-carbon transformation, as it was presented in scenario 5. Economic and societal commitment is also required.

In addition, the results of the macroeconomic approach were combined with the results of the sociological approach. The generated interdisciplinary insights on the transformation towards a low-carbon economy through gas infrastructure modification were published in the Hoffart at al. [HOF20b].

Figure 3.6 shows what these key messages mean in more detail and displays the overall level of transformation, the level of engagement and the level of conflict in a graphical way. First, comparing the two best-case scenarios, namely scenario 2 and scenario 3, with scenario 5 shows that the same level of engagement does not necessarily lead to the same level of overall transformation. While scenario 2 and scenario 3 result in a high level of transformation, the transformation level of scenario 5 is medium. The difference can be explained by the level of conflict, which is high for scenario 5, low for scenario 3 and medium for scenario 2. The potential for conflicts can result both from divergent interests and from the absence of a common vision of the future. As a result, the high amount of resources and the high commitment of all stakeholder groups cannot be translated into a high level of progress in terms of the low-carbon transformation. Scenario 5 shows the same level of transformation as scenario 4, the *incremental green transformation*, where both the level of engagement (medium) and the level of conflict (low) are smaller. Second, while a high level of conflict is a hindering factor for a high level of transformation, as scenario 5 shows, a low (or medium) level of conflict is a necessary, but not sufficient, condition. In scenario 1, the *fossil revival instead of green progress*, the level of conflict is ranked as low, as well as the level of engagement, which explains the low level of transformation. Third, without a high level of engagement, a high transformation level is not possible, although this condition is not sufficient.

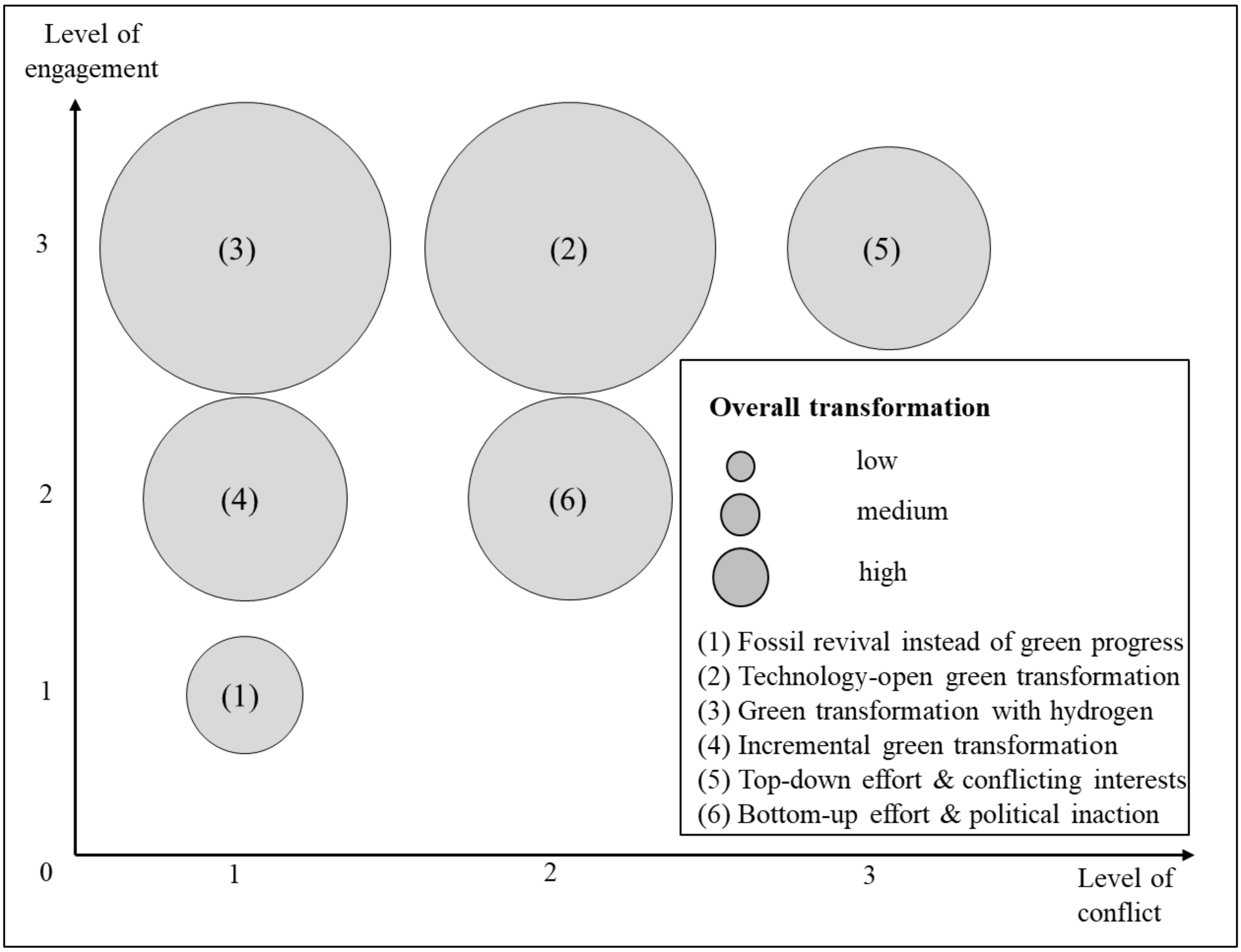


Figure 3.6: The system dynamics of the qualitative scenarios.
Source: Author's own contribution.

3.3 Part 2: Scenario-based infrastructure evaluation

3.3.1 Analysis of infrastructure key requirements

To prepare for the scenario-based interdisciplinary infrastructure evaluation, three discipline-specific workshops took place. In this workshop, the core scenario team identified, together with representatives of each discipline, three key requirements that are for the respective discipline important for the realization of each infrastructure option. These key requirements are based on the research of the individual disciplines and were translated into a scenario language. The economic key requirements were identified by the core scenario team.

Going more into detail, the technical workshop revealed that no purely technical requirements are considered critical for the realization of one of the infrastructure options (see section 2). This feedback from the discipline of engineering is in line with the approach's understanding of feasibility, as well as with the results of the key factor analysis and the scenario interpretation. To adjust to this feedback, the discipline's key requirements cover instead of technical aspects techno-economic aspects, which determine the feasibility from an engineering perspective. To avoid overlaps with the economic perspective, the economic key requirements concentrate on a broader rather market-oriented macroeconomic perspective.

Table 3.7, Table 3.8 and Table 3.9 list all key requirements and provide a short explanation for each of them. The numbering of the key requirements provides information to what infrastructure option and discipline the respective requirements belongs to. For reasons of understandability, the numbering of the key requirements is always mentioned. The numbering of the key requirement *2.7 Competitiveness of* H_2, e.g., implies that it refers to Infrastructure option 2 and the macroeconomic perspective. The integration of the individual disciplines' perspectives represents a key characteristic of the German case study. It allows to evaluate the three infrastructure options from an interdisciplinary perspective with a common framework that translates the qualitative input in form of key requirements in quantitative and comparable consistency scores. By doing so, all disciplines are weighted as equally important. In a next step, the key requirements were analysed in more details.

First, the different disciplines were asked to match their key requirements to three system levels, namely *infrastructure for* H_2*/CCS, Market for* H_2*/CCS* and *Market enabler*. The results can be seen in Figure 3.7 and demonstrate that the feasibility of a H_2/CCS infrastructure does not only depend on aspects related to the infrastructure itself. Other aspects, such as the existence and development of a H_2/CCS market, are crucial, which is in line with the macroeconomic approach, the idea of the system image and the understanding of feasibility. Considering the different levels, 39% of key requirements refer the *infrastructure for* H_2*/CCS*, 36% to the *Market for* H_2*/CCS* and 25% to the *Market enabler*. Looking into the different infrastructure options, all levels are covered. The same does apply for the sociological and techno-economic key requirements. While the macroeconomic key requirements do not apply to the level *infrastructure for* H_2*/CCS*, the legal key requirements do not concern the *market enabler*.

Second, the different disciplines were asked to assess the chances of realization and the related costs for the fulfilment of the key requirements based on their research and expertise. The costs, however, do not only refer to financial means, but cover required resources in general including, e.g., personal resources for negotiations or transaction costs. Besides, the core scenario team matched involved stakeholders to each key requirement. The results are exemplarily displayed for infrastructure option 3 in Table 3.10. The stakeholder groups are represented by the number of the related key factor. To provide an example, for the realization of the sociological key requirement *3.4 Acceptance of* H_2 *pipelines*, security and insurance aspects as well as options for participation are important. Therefore, not only monetary incentives to satisfy e.g. citizens who protest against new pipelines are required, but also options for participation. Participation is time-intensive in terms of planning, and the event itself and requires not only financial resources, but also personal resources and know how. *Citizens and society (#8)* are involved as primary actors, as well as *public interest groups (#7)*, which mainly contribute as trusted organization to public opinion. Furthermore, *political decision makers (#22)* are indirectly involved as they determine the legislation for mandatory participation related to infrastructure projects. The level of costs was rated as rather high, since many stakeholders are involved in the realization of the key requirements, which is both resource and cost-intensive and requires a change of mind. The chance of realization is estimated to be rather high, too. In the case that the required resources are available, acceptance for H_2 pipeline also is rather high [GLA20].

Table 3.7: Key requirements infrastructure option 1.

Option 1: CO_2 pipelines to export CO_2 for off-shore CCS			
#	*Key requirement*	*Perspective*	*Explanation*
1.1	Removal of CO_2 export ban	legal	To enable CO_2 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 CO_2 network implementation	legal	CO_2 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 CO_2 networks	legal	The legal framework to specific challenges of CO_2 pipeline networks on EU and national level has to be adjusted: coordination of CO_2 stream quality, harmonization of legal requirements, safety ordinance.
1.4	CCS with industrial applications and BECCS	sociological	Acceptance of CCS related 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 decarbonize fossil fuel, especially coal power plants.
1.5	Acceptance of CO_2 pipelines	sociological	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	sociological	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	macro-economic	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 CO_2 transport and storage	macro-economic	A market that offers cross-border CO_2 transport and storage at affordable costs and adequate conditions is required.
1.9	Incentives for carbon capture	macro-economic	To incentivize carbon capture, related costs need to be smaller than the costs of CO_2-emissions. Besides the costs of emission certificates, the electricity price is important.
1.10	Future perspective for CO_2 capture and steam availability	techno-economic	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 local at low costs.
1.11	Low-cost CO_2 pipelines	techno-economic	For CO_2 transport to be economically attractive, costs for new CO_2 pipelines are important. To reduce costs of CO_2 pipelines, multiple booster stations allow for a lower diameter, which is cheaper.
1.12	CO_2 transport scaling-effects	techno-economic	To decrease the costs of CO_2 transport and to allow for synergies, local industry clusters aiming at joint CO_2 transport are needed.

Source: Author's own contribution.

Table 3.8: Key requirements infrastructure option 2.

Option 2: H_2 admixture in the natural gas grid			
#	*Key requirement*	*Perspective*	*Explanation*
2.1	Cost allocation of blue H_2 production	legal	Costs and benefits of CO_2 mitigation, related to the production of blue H_2 including CCS, have to be allocated in a suitable way.
2.2	Clarification of gas definition	legal	To clarify the application of EnWG provisions (third party access) to blue H_2, a clear gas definition in the EnWG is needed.
2.3	Coordination of gas quality	legal	To significantly raise the amount of H_2 in transmission pipelines, high level coordination is required to ensure the compatibility of gas quality.
2.4	Acceptance of pipeline retrofitting	sociological	Acceptance of pipeline retrofitting is required. For acceptance, security and insurance issues as well as options of participation are important.
2.5	Synergies with renew. energy systems	sociological	Green H_2 is preferred over blue and grey H_2. A linkage to renewable energy systems increases the acceptance for H_2 in general.
2.6	Acceptance for H_2	sociological	Acceptance of H_2 as an energy carrier is required and depends on the opinion of public interest groups and openness towards new technologies.
2.7	Competitiveness of H_2	macro-economic	For H_2 as a substitute for fossil fuels and energy, H_2 needs to be competitive with natural gas.
2.8	H_2 demand for admixture	macro-economic	From the supply side (grid operators), there needs to be a demand of H_2 admixture, which requires a retrofitting but also usability for industrial applications.
2.9	Supply for H_2 admixture	macro-economic	Suppliers are needed, who provide and sell H_2 for admixture at a reasonable amount and price.
2.10	Incentive to inject H_2	techno-economic	For an admixture, H_2 needs to be competitive to natural gas. A higher CO_2 price incentivizes the decarbonization of the natural gas grid and increases the demand for H_2 admixture.
2.11	Constant H_2 admixture <30%	techno-economic	For a constant H_2 level, multiple injection points are needed and can be served by an H_2 network. For compatibility reasons of end users, the H_2 level should stay below 30% or switch to 100%.
2.12	Investments in pipeline retrofitting	techno-economic	Investments in the adjustment of the existing gas infrastructure to a higher level of H_2 are required and need to be incentivized.

Source: Author's own contribution.

Table 3.9: Key requirements infrastructure option 3.

Option 3: New H_2 network			
#	*Key requirement*	*Perspective*	*Explanation*
3.1	Non-discrimination of blue H_2	legal	The relative disadvantage of blue H_2 compared to natural gas under the EU ETS should be eliminated
3.2	Legal regime for H_2 pipelines	legal	The legal regime for dedicated H_2 pipelines needs to be clarified.
3.3	H_2 tariffs regulation	legal	Tariffs regulation is demanded to hedge market participants (especially grid customers).
3.4	Acceptance of H_2 pipelines	sociological	Feasibility of H_2 requires acceptance of related pipelines. For acceptance, security and insurance issues as well as options for participation are important.
3.5	Synergies with renew. energy systems	sociological	Green H_2 is preferred over blue and grey H_2. A linkage to renewable energy systems increases the acceptance for H_2 in general.
3.6	Acceptance of H_2	sociological	Acceptance of H_2 as an energy carrier is required. Acceptance for H_2 depends on the opinion of public interest groups and openness to new technologies.
3.7	Governmental market incentives	macro-economic	To establish hydrogen as a dominant future energy carrier, a national hydrogen strategy and economic incentives, e.g. subsidies, are required.
3.8	High demand for H_2	macro-economic	A high demand and use of H_2 throughout all sectors and industries is needed. The H_2 demand depends on H_2 price, the availability of applications and infrastructure.
3.9	High supply for H_2	macro-economic	A high H_2 supply is needed to satisfy the demand, to enable a H_2 market and to incentives investments to adapt end-user and industry applications to H_2. A nationwide H_2 infrastructure is also needed.
3.10	Competitiveness of H_2 technologies & applications	techno-economic	To generate the need for an H_2 infrastructure, H_2 technologies and application in industry, heating and mobility need to be competitive to competing technologies (e.g. electro-cars).
3.11	Low-cost H_2 pipelines	techno-economic	To enable low-cost pipelines, further recompression should be avoided due to high compressor costs. Additional costs can also result from delays related to protests and need to be considered.
3.12	Infrastructure synergies through industry hotspots	techno-economic	Industrial hotspots are main drivers of H_2. They bring H_2 to a region and thus stimulate H_2 demand of other sectors. Related infrastructure synergies allow to link other local sectors.

Source: Author's own contribution.

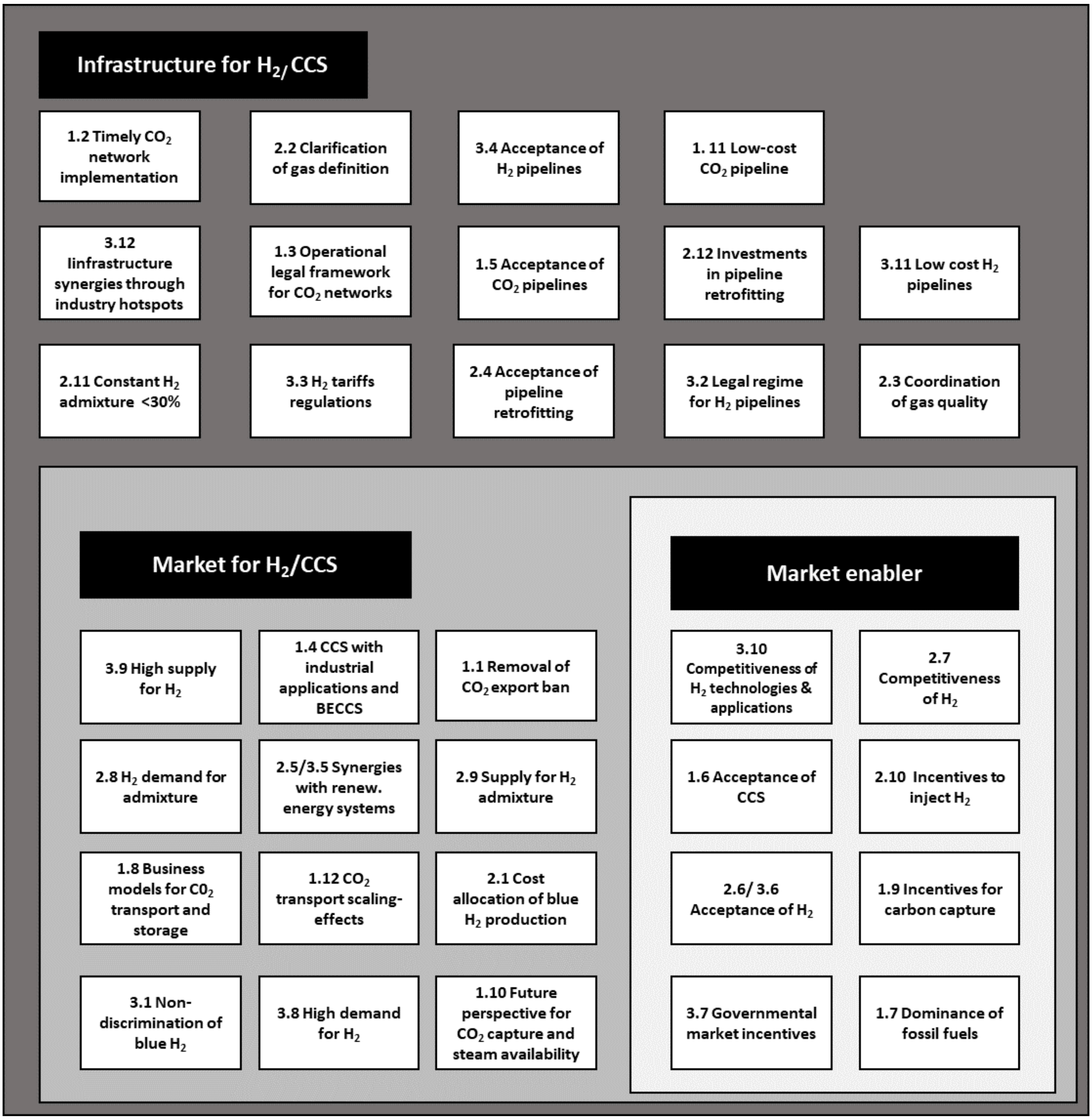


Figure 3.7: Overview of key requirement and related system levels.
Source: Author's own contribution.

Table 3.10: Stakeholder and feasibility assessment of infrastructure option 3.

#	*Key requirement*	*Perspective*	*Realization*	*Costs*	*#7*	*#8*	*#15*	*#21*	*#22*
3.1	Legal regime for H_2 pipelines	legal	high	medium			x		x
3.2	Non-discrimination of blue H_2	legal	medium	low					x
3.3	H_2 tariffs regulations	legal	high	low			x	x	x
3.4	Acceptance of H_2 pipelines	sociological	medium	high	x	x			x
3.5	Synergies with renew. energy systems	sociological	high	low	x	x	x	x	x
3.6	Acceptance of H_2	sociological	high	low	x	x			
3.7	Governmental market incentives	macroeconomic	high	high					x
3.8	High demand for H_2	macroeconomic	medium	medium	x			x	x
3.9	High supply for H_2	macroeconomic	high	medium				x	x
3.10	Competitiveness of H_2 technologies & applications	techno-economic	medium	medium			x	x	x
3.11	Low-cost H_2 pipelines	techno-economic	medium	medium	x	x		x	x
3.12	Infrastructure synergies through industry hotspots	techno-economic	high	low			x	x	

Source: Author's own contribution.

In a next step, critical key requirements were distilled based on the estimated chance of realization. As Figure 3.8 shows, supportive and hindering key requirements can be differentiated, which are either high or low in costs. While *supportive* implies a high chance of realization, *hindering* refers to a low chance. Thus, three types of critical key requirements - namely low-cost supportive requirements, high-cost supportive requirements and high-cost hindering requirements – were revealed to be crucial.

In general, 15 critical key requirements were identified, of which the great majority (10 out of 15) represents supportive key requirements. This result can be interpreted as a positive sign for the feasibility of all three infrastructure options. Interestingly, 90% of all supportive key requirements mainly refer to infrastructure option 2 and infrastructure option 3, whereas 4 out of 5 hindering requirements refer to infrastructure option 1. The majority of supporting low-cost requirements are sociological key requirements and refer to the two hydrogen-based infrastructure options 2 and 3. While no techno-economic key requirements has a hindering effect, 3 out of 5 hindering factors are macroeconomic factors, applying mainly to infrastructure option 1 and infrastructure option 2.

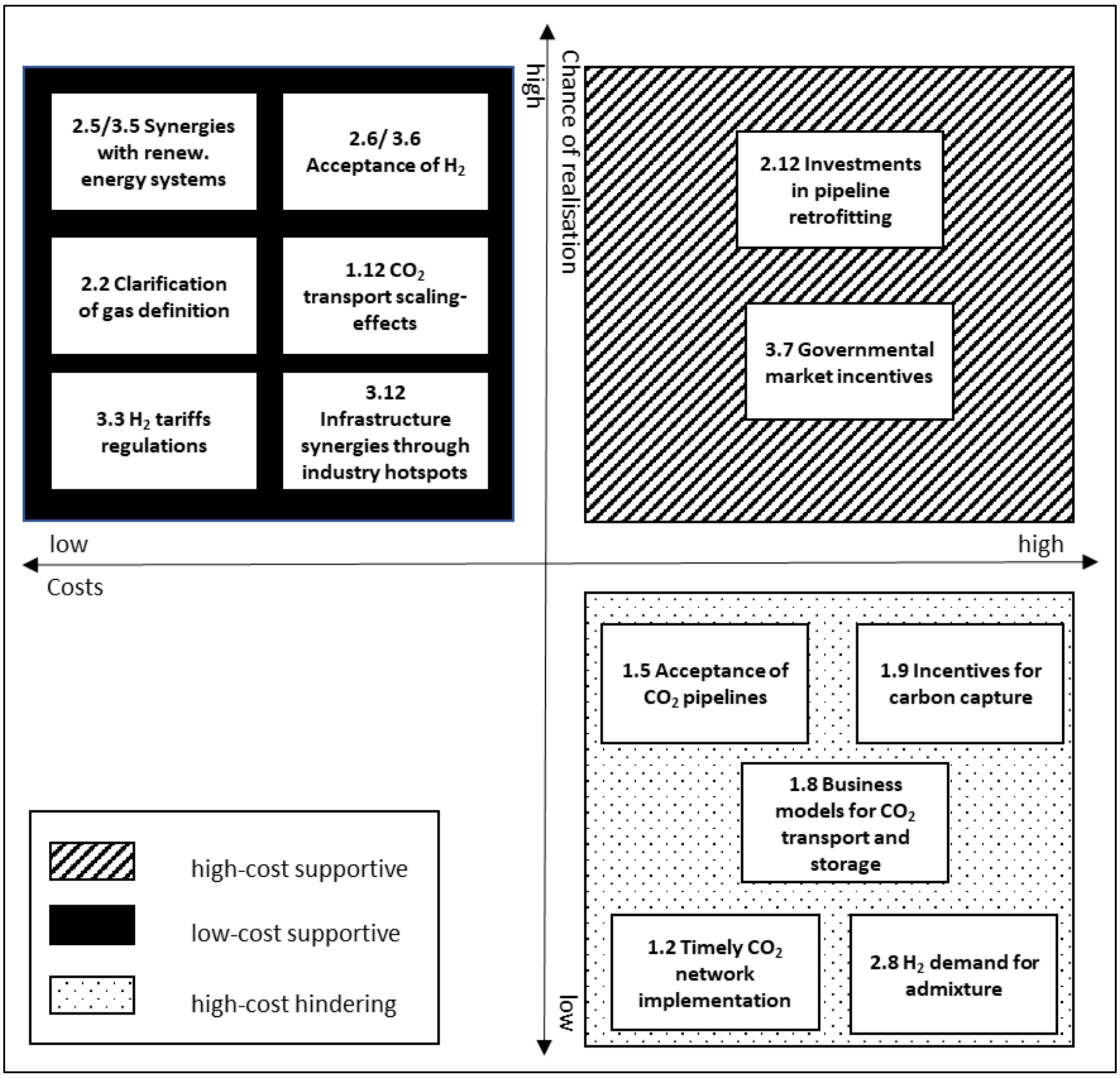


Figure 3.8: Critical key requirements.
Source: Author's own contribution.

One example is *1.8 Business models for CO_2 transport and storage*. From an economic perspective, the feasibility of CCS in general is rather low in Germany. Even if the public acceptance of CCS (see key requirement *1.6 Acceptance of CCS*) would increase, and the export of CO_2 would be possible (see key requirement *1.1 removal of CO_2 export ban*), business options for cross-border CO_2 transport and storage are required to enable infrastructure option 1. Besides the issues of acceptance and CO_2 export, unclear questions arise indicating a high level of complexity: will CO_2 be sold as a good or as a waste product? Who builds the pipelines to the CO_2 producer? Who is responsible if the CO_2 leaks from the pipelines or from the underground storage? How much storage capacity is available for how long and to what price? Thus, the development of a market for such services at affordable costs and adequate conditions is regarded as rather low. Similarly, the chance of an adequate *2.8 H_2 demand for admixture* relevant for infrastructure option 2 are expected to be rather low. Currently, H_2 is regarded as an expensive good compared to natural gas. To realize infrastructure option 2, a constant admixture of H_2 into the natural gas network is required to guarantee a constant level of H_2 (See requirement *2.1 Constant H_2 admixture <30%)*. Multiple injection points or a separate H_2 network functioning as a backbone is needed. Therefore, it is necessary that suppliers of H_2 provide the required amount of H_2 (see

2.9 Supply for H_2 admixture). The availability of supply depends on the price for H_2 admixture, which is determined also by the demand for H_2 admixture. Since natural gas is currently cheaper than H_2 and as investments to adjust application to a higher level of H_2 are required, as well as H_2 is disadvantageous compared to natural gas in the EU ETS (see *3.1 Non-discrimination of blue H_2*), the demand is expected to be rather low. Thus, selling pure H_2 instead of admixturing it into the natural gas grid would result in a higher market price. This example demonstrates the value added of the interdisciplinary approach. Without the exchange for identifying the key requirements, the understanding of this hindering key requirement would remain incomplete. The explanation of the issue includes macro-economic, legal as well as techno-economic aspects that jointly provide a picture of the issue at discussion. The sociological key requirement *2.4 Acceptance of pipeline retrofitting* would be mentioned to further extent the issue. The complexity and interconnectedness of the different disciplines further support the approach's understanding of feasibility.

Furthermore, the sociological key requirement *3.4/2.4 Acceptance of H_2* can be mentioned as an example of supportive low-cost requirements related the two H_2 infrastructure options 2 and 3. As the related costs are rather low and as the chance of realization is rather high, such key requirements represent so-called low-hanging fruits, which can be realized without big effort. As the sociological results show (see section 5), the acceptance of H_2 is rather high and depends inter alia on the trust in and on the influence of public interest groups and the existing options for participation.

As a macroeconomic supportive, but high-cost requirement, *3.7 Governmental market incentives* can be mentioned. To realize infrastructure option 3, a separate H_2 infrastructure, an H_2 market with a high level of H_2 demand (see key requirements 3.8) and a high level of H_2 supply (see key requirements 3.9) are required. To establish H_2 as a dominant future energy carrier, market incentives provided by the government, such as a national hydrogen strategy or economic subsidies, are essential. As both the recently published German and European H_2 strategies, which set important incentives, show, the chance of realization is rather high. The costs for both the development and realization of such strategies are, however, rather high. Personal resource for time-consuming negotiations, as well as financial means to provide extensive subsidies are required.

While the analysis of key requirements implicitly builds on the future expectation of the experts from the different case study disciplines, the scenario-based interdisciplinary infrastructure assessment is future robust, as the next section will show.

3.3.2 Interdisciplinary infrastructure and stakeholder analysis

For the scenario-based interdisciplinary infrastructure evaluation, the core scenario team performed a consistency analysis. For each key requirement, the consistency with each scenario was assessed resulting in total of 216 individual consistency scores. The consistency analysis for infrastructure option 3 is shown exemplary in Table 3.11.

In a next step, the consistency values were aggregated for a final assessment. Table 3.12 shows the different consistency values for each infrastructure option (average overall consistency), for each scenario (overall consistency) and for each discipline (average consistency) at different level of aggregation. The discipline-specific values represent the average value of the three key requirements' consistency.

Table 3.11: Scenario-based evaluation of infrastructure option 3.

#	***Key Requirements (related key factor)***	***S (1)***	***S (2)***	***S (2)***	***S (4)***	***S (5)***	***S (6)***
legal perspective							
3.1	Non-discrimination of blue H2 (#4, #15, #23)	1	5	5	4	5	2
3.2	Legal regime for H2 pipelines (#22)	1	5	5	2	3	2
3.3	H2 tariffs regulation (#23 #22)	1	4	5	2	5	3
sociological perspective							
3.4	Acceptance of H2 pipelines (#14, Option for participation)	1	4	5	4	4	3
3.5	Synergies with renew. energy systems (#11, #6, #16)	2	5	5	4	3	4
3.6	Acceptance of H2 (#9, #18, #7)	2	5	5	4	2	4
macroeconomic perspective							
3.7	Governmental market incentives (#23, #2)	1	4	5	3	3	4
3.8	High demand for H2 (#9, #18, #3)	1	5	5	3	4	5
3.9	High supply for H2 (#16, #11, #14)	1	5	5	4	5	4
techno-economic perspective							
3.10	Competitiveness of H2 technologies & applications (#23, #15, #3)	1	5	5	3	4	4
3.11	Low-cost H2 pipelines (#14, #21, Option for participation)	1	4	4	3	3	4
3.12	Infrastructure synergies through industry hotspots (#14, #21, #15)	1	5	5	2	2	4

1= highly inconsistent, 2= partly inconsistent, 3= unclear consistency, 4= consistent, 5= highly consistent

Source: Author's own contribution.

Considering all six socio-technical scenarios, the average overall consistency values generated for each infrastructure option reveal that infrastructure option 3 is the most consistent one (3.5). A positive consistency of 3.5 implies that option 3 is the most feasible infrastructure compared to option 2 (3.4) and option 1 (3.0). Notably, the difference between infrastructure option 2, *admixture of* H_2, and infrastructure option 3, *a separate* H_2 *network*, is very small, while the difference to infrastructure option 1, CO_2 *pipelines for off-shore CCS*, is bigger. It implies that infrastructure option 3 is slightly more feasible compared to infrastructure option 2. Infrastructure option 1 was identified to be the least feasible infrastructure option. To be more precise, a value of 3 implies for option 1 that it is unclear whether a CO_2 infrastructure is positively or negatively consistent and, thus, feasible or not.

Looking at the different socio-technical scenarios, all infrastructure options are most consistent and thus feasible with either scenario 2 or scenario 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 value, which is greater than or equal to 4. While the highest overall consistency level (4.9) results from infrastructure option 3 in combination with scenario 3 – *green transformation with* H_2, the lowest overall consistency level (1.2) refers to infrastructure option 3 combined 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 requirement.

Table 3.12: Consistency analysis & infrastructure evaluation.

Scenarios	***Overall consistency***	***legal***	***sociological***	***macro-economic***	***techno-economic***
	Option 1				
(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				
(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				
(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 own contribution.

Infrastructure option 1: CO_2 pipelines for off-shore CCS

Infrastructure option 1 shows the highest overall consistency level with scenario 2 (4.1) – the *technology-open green transformation*. In scenario 2, all individual key requirements are consistent (4 or 5) except key requirement *1.7 dominance of fossil fuels*, which has the lowest consistency value (1). Infrastructure option 1 is the least feasible with scenario 1 (2.3) – *fossil revival instead of green progress* - and scenario 6 (2,3) – *Bottom-up effort & political inaction*.

The value of 2.3 related to scenario 2 and scenario 6 indicates a negative consistency and thus low or negative feasibility. Comparing the different disciplines, the macroeconomic key requirements are the most limiting (2.6) and show an, on average, negative consistency, while the legal key requirements are the most supportive, meaning a positive consistency of 3.5. Going more into detail, the macroeconomic key requirements *1.8 business models for CO_2 transport and storage* and *1.9 incentives for carbon capture* are the most critical with an averagely negative consistency level of 2.3. The legal key requirement *1.1 removal of CO_2 export ban* is the most consistent with an on average positive consistency level of 3.8.

While the presented consistency values are future-robust and apply to all scenarios, the critical key requirements refer to the discipline-specific expectations. Considering the latter, the following three out of four 'low feasibility and high cost'-requirements, meaning costly hindering factors, refer to option 1: *1.2 Timely CO_2 network implementation, 1.8 Business models for CO_2 transport and storage, 1.5 Acceptance of CO_2 pipelines, 1.9 Incentives for carbon capture.* Besides, only one out of eight high feasibility and low-cost requirements, namely *1.12 CO_2 transport scaling effects*, belongs to infrastructure option 1.

From a stakeholder perspective, *political decision makers* (#22) are involved the most in infrastructure option 1, followed by the *citizens & society* (#8) and *investors (#21*). Compared to the other infrastructure options, the most stakeholder groups are involved in the fulfilment of the key requirements related to infrastructure option 1. These results also explain this infrastructure option's low level of feasibility, as a lot if interaction and thus conflict between the stakeholder groups exists.

Infrastructure option 2

Infrastructure option 2 shows the highest overall consistency level with scenario 3 (4.8). In scenario 3, *green transformation with hydrogen*, the legal and the macroeconomic key requirements each show the maximal possible average consistency level of 5. It means that these requirements are highly consistent and thus highly feasible in the respective scenario. Contrarily, the *H_2 admixture into the natural gas grid* is the least consistent and thus feasible in the fossil dominated scenario 1. The legal and macroeconomic key requirements each show an on average consistency level of 1.0, which is the smallest consistency possible. Throughout all scenarios, the sociological key requirements are the most supportive (3.7) for infrastructure option 2, which is also the highest on average consistency level of all disciplines. The other disciplines' key requirements each show the same on average consistency level of 3.3.

Looking at the individual key requirements, on the one side, the legal key requirement *2.1 Cost allocation of blue H_2 production* is the least consistent and thus most critical key requirement of infrastructure option 2. On the other side, the sociological key requirement *2.5 Synergies with renew. energy systems* and *3.6 Acceptance of H_2* are the most consistent and thus supportive.

Considering the critical key requirements determined by the expectations of each discipline, one out of four low-feasibility and high-cost requirements refers to option 2, namely *2.8 H_2 demand for admixture*, as well as 1 out of 2 high feasibility and high-cost requirements, namely *2.12*

Investments in pipeline retrofitting. Besides, the following high-feasibility and low-cost requirements belong to option 2: *2.2 Clarification of gas definition, 2.6 Acceptance of H_2, 2.4 Synergies with renew. energy systems.*
In option 2, the least stakeholders are involved compared to the other two infrastructure options. Again, *political decision makers* (#22) are the most important stakeholder group, which is important in 10 out of 12 key requirements, followed by *investors* (#21), who are only relevant for 5 out of 12 key requirements.

Infrastructure option 3: A separate H_2 network
Option 3 shows the highest overall consistency level with scenario 3 (4.9) and the lowest, negative overall consistency with the fossil dominated scenario 1 (1.3). In scenario 3, the *green transformation with hydrogen*, the legal, sociological and macroeconomic key requirements each show an on average consistency level of 5. It implies that all key requirements, except for the techno-economic key requirements *3.11 Low-cost H_2 pipelines* (4) and *3.12 Infrastructure synergies through industry hotspots (4)* are highly consistent (5). Contrarily, a *separate H_2 network* is least consistent and thus feasible in the fossil dominated scenario 1, which shows the lowest overall consistency value (1.2). Except for the sociological key requirements, which display an on average consistency level of 1.7, all key requirements are highly inconsistent (1). It means that the realization of the related key requirements in the respective option is rather not feasible.
Considering the different disciplines' key requirements, the sociological and macroeconomic key requirements are the most supportive ones (3.7). The legal key requirement *3.2 Legal regime for H_2 pipelines* and the techno-economic key requirement 3*.12 Infrastructure synergies through industry hotspots* are the most critical (3.0), whereas the sociological key requirements *3.5 Synergies with renew. energy systems*, *3.6 Acceptance of H_2* and the macroeconomic key requirement *3.8 High demand for H_2* are the most supportive (3.8).
Looking at the key requirements based on the disciplines' expectations, the following four out of eight high-feasibility and low-cost key requirements refer to option 3: *3.3 H_2 tariffs regulation, 3.5 Synergies with renew. energy system, 3.6 Acceptance of H_2, 3.12. Infrastructure synergies with industry hotspots.* Additionally, the key requirement *3.7 Governmental market incentives* was identified as a high-feasibility and high-cost requirement, meaning a supportive but expensive factor. The fact that 5 supportive requirements refer to option 3, and respectively 4 to infrastructure option 2, explains why the difference in terms of feasibility is so small between the H_2 admixture and a separate H_2 network.
From a stakeholder point of view, *political decision-makers* (#22) are involved the most, followed again by *investors* (#21).

3.4 References

[BIS07] Bishop, P.; Hines, A.; Collins, T. et al.: *The current state of scenario development. An overview of techniques*. In: *Foresight* 9 Nr. 1, pp. 5–25, 2007.

[BRA05] Bradfield, R.; Wright, G.; Burt, G. et al.: *The origins and evolution of scenario techniques in long range business planning*. In: *Futures* 37 Nr. 8, pp. 795–812, 2005.

[GAU89] Gausemeier, J.; Fink, A.; Schlanke, O. et al.: *Scenario management: An approach to develop future potentials*. In: *Technological Forecasting and Social Change* 59 Nr. 2, pp. 11-130, 1998.

[GLA20] Glanz, S., Schönauer, A.-L. *Towards a Low-Carbon Society via Hydrogen and Carbon Capture and Storage: Social Acceptance from a Stakeholder Perspective*, In: *J. sustain. dev. energy water environ. syst.2020.* doi: http://dx.doi.org/10.13044/j.sdewes.d8.0322.

[GRU02] Grunwald, A.: *Technikfolgenabschätzung. Eine Einführung*. Berlin: Ed. Sigma. 2002. (Gesellschaft - Technik - Umwelt, N.F., 1) - ISBN: 3894049316.

[HOF20a] Hoffart, F. M.; Schmitt, E-J.; Roos, M. W.M.: *Rethinking Economic Energy Policy Research – Developing Qualitative Scenarios to Identify Feasible Energy Policies.* In*: J. sustain. dev. energy water environ. syst..2020.* doi: http://dx.doi.org/10.13044/j.sdewes.d8.0331.

[HOF20b] Hoffart, F. M.; Glanz, S; Span, R.; Schönauer, A.-L.: M.: *Transition towards a Low-Carbon Economy through Gas Infrastructure Modification – Economic and Sociological Interdisciplinary Insights.* In*: Energy Proceedings.* 2020. Vol 2: Proceedings of 11th International Conference on Applied Energy, Part 1, Sweden.

[KOS08] Kosow, H.; Gaßner, R.: *Methods of future and scenario analysis. Overview, assessment, and selection criteria*. Bonn: Dt. Inst. für Entwicklungspolitik. 2008. (Studies / Deutsches Institut für Entwicklungspolitik, 39) - ISBN: 9783889853752.

[MCI14] McInerny, G.J., Chen, M., Freeman, R., Gavaghan, D., Meyer, M., Rowland, F., Spiegelhalter, D.J., Stefaner, M., Tessarolo, G. and Hortal, J., *Information visualisation for science and policy: Engaging users and avoiding bias.* In: *Trends Ecol. Evol. (Amst)*, Vol. 29, No. 3, pp. 148–157, 2014.

[ROO07] Roos, M. W.M.: *Nonexpert beliefs about the macroeconomic consequences of economic and noneconomic events*, In: *Public Choice* 132 (3-4), pp. 291-304, 2007.

[ROO15] Roos, M. W.M..: *Die Komplexitätsökonomik und ihre Implikationen für die Wirtschaftspolitik*. In: *Perspektiven der Wirtschaftspolitik* 16(4), pp. 379-392. 2015.

[SCH15] Schubert D.K.J., Thuß, S. and Möst, D.: *Does political and social feasibility matter in energy scenarios?* In*: Energy Research & Social Science*, Vol. 7, pp. 43–54, 2015.

4 LEGAL ASPECTS

To contribute to the assessment of the feasibility of the three infrastructure options, the relevant legal framework – specifically in respect of the creation of the respective infrastructure, its operation and its interaction with markets and marketing – is examined. Especially, costs, risks and barriers for the options that result from the legal framework are identified and analysed. This works focuses of the specific provisions and issues in regard to the three infrastructure options (in contrast to general issues for large infrastructure projects in general or natural gas pipelines in particular). Additionally, possible remedies, mainly potential legislative actions, are discussed. This discussion is the basis for recommendations, especially for legislative actions.

4.1 Base Option 1: CCS Pipelines

4.1.1 Legal Background

The **legal background** for CO_2 pipelines for CCS is dominated by the Carbon Dioxide Storage Act (KSpG), which implements Directive 2009/31/EC (CCS Directive). Especially § 4 KSpG with its references to other stipulations of the KSpG as well as to stipulations in the Energy Industry Act (EnWG) and in the Federal Administrative Procedures Act (VwVfG) addresses CO_2 pipelines. Further specific provisions for CO_2 pipelines can be found in the Environmental Impact Assessment Act (UVPG) in regard to the need of environmental impact assessments, in the Greenhouse Gas Emission Trading Act (TEHG) in regard to the application of the EU emission trading system (EU ETS), in Regulation (EC) 1013/2006 (Shipments of Waste Regulation) in regard to the export of CO_2 for CCS, and in Regulation (EU) 347/2013 (TEN-E Regulation) in regard to CCS projects as projects of common interest (PCIs) in their current form respectively. Additionally, where there is no special provision on CCS, general environmental and plant law applies.

The **KSpG** covers most relevant aspects of CO_2 pipelines for CCS, including safety regulation, administrative procedure for construction, expropriation, liability, major accidents, access and tariffs. Yet, due to the focus of the KSpG on the storage rather than the transportation of CO_2 and due to the rejection of CCS in Germany, the actual provisions are rather rudimentary as well as partially inappropriate and misleading [BEN20b]. Especially, ordinances based on the KSpG were never enacted.

Furthermore, pursuant to its no. 19.10 Annex I, the UVPG, which implements Directive 2011/92/EU (EIA Directive), stipulates the need for environmental impact assessments and preliminary assessments for CO_2 pipelines, depending on their size [BEN19]. The TEHG, which implements Directive 2003/87/EC (EU ETS Directive), demands allowances also for emissions by CO_2 pipelines for CCS, see Annex I part 2 no. 31 TEHG. Pursuant to article 1 (3) lit. h) Shipments of Waste Regulation, the shipment of waste regime, including the reference to international agreements like the 1996 London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol), is extended to CO_2 for CCS. And the TEN-E Regulation defines CO_2 pipelines for CCS as energy infrastructure and allows identifying them as PCIs. The application of general environmental and plant law ensures that environmental and third party interests have to be observed.

CO_2 pipelines are covered by a clear and specific legal regime both at EU and national level. Yet, the quality of this regime exhibits some weaknesses, especially due to limited political will of the German legislator and government to develop it further.

4.1.2 Construction

4.1.2.1 Legal Requirements for Construction

The legal requirements for both the pathway and the design of CO_2 pipelines in Germany are dominated by § 4 (3) sentence 2 KSpG, which essentially refers to § 49 EnWG, which stipulates the **safety requirements** for natural gas pipelines. Thus, the legal requirements for natural gas and CO_2 pipelines are in principal congruent. Yet, the concrete requirements for (new) CO_2 and (well established) natural gas pipelines differ drastically, mainly due to two reasons. First, the special hazards connected to CO_2 pipelines ask for respective measures. There is no danger that CO_2 will explode (which is the major concern in regard to natural gas pipelines). However, CO_2 that is set free from CO_2 pipelines in a major accident has a suffocating and freezing effect, CO_2 (unlike natural gas) flows on the ground until it evaporates, defects on a CO_2 pipeline can be accompanied by a running ductile fracture, impurities in CO_2 pipelines have to be observed and may even interact (creating new hazards), and CO_2 transportation poses specific challenges in regard to corrosion [BUN18; MAH20]. Secondly, § 49 EnWG refers to the technical rules of the Deutsche Vereinigung des Gas- und Wasserfaches e. V (DVGW). For natural gas, the compliance with the required safety is assumed if these rules are complied with (if not proven otherwise). Therefore, the technical rules of the DVGW have a prominent actual relevance for the safety requirements, substantially facilitating the application of the legal safety requirements. For CO_2, there are no technical rules by the DVGW yet; therefore, the safety of the planned CO_2 pipelines has to be independently proven case-by-case. The lack of technical rules is not just a formalistic hurdle that can easily be removed; rather it is an expression of remaining scientific and technical uncertainties in regard to the risks of CO_2 pipelines and the possible ways to handle these risks, which have to be observed by pipeline planners. Although CO_2 pipelines are an established technology in the context of enhanced oil recovery (EOR) (especially in the USA), there is little experience in the context of CCS networks and in respect of the special legal requirements in regard to the environment and densely populated areas in Europe; further research is needed and underway. The currently remaining uncertainties can be handled by more conservative assumptions in regard to design and pathways, which can increase costs. The more CO_2 pipelines for CCS are tested and understood, the easier the safety of planned pipelines can be proven and the less unnecessary costs have to be borne.

Additionally, for the construction of a **cross-border CO_2 pipeline**, § 4 (2) sentence 3 KSpG provides the specific requirement that the storage site to which the CO_2 is transported complies with the requirements of the CCS Directive. Since the relevant destination sites are in the Netherlands and therefore have to comply with the CCS Directive, this requirement is not an issue.

In the context of **general environmental law**, there are no requirements that have to be specifically observed for CO_2 pipelines. Especially, since CO_2 is not water-pollutant, the respective restrictions in regard to water protection have not to be observed. Yet, some impurities in CO_2 rich mixtures for CCS may be water-pollutant; this aspect may lead to a noteworthy interaction of the acceptable CO_2 stream quality and possible pipeline pathways and designs.

Legally, the general requirements for CO_2 pipelines are not connected to specific issues of great import. However, the actual behaviour and properties of CO_2 in CO_2 pipelines, which is markedly different from that of natural gas, and the remaining scientific and technical uncertainties (in the context of CO_2 networks in Europe) create specific challenges in respect of the safety requirements. It is much harder for planners of CO_2 pipelines to prove and document that the technical specifications and the pathway of the pipelines are sufficiently safe. This aspect has to be observed, while there is little that can be legally done.

4.1.2.2 Permitting Procedure

For all CO_2 pipelines for CCS – including small pipelines –, the construction has to be permitted pursuant to the **planning decision** regime, see § 4 (1) KSpG. The planning decision procedure is a special procedure, which concentrates different permitting procedures and in general demands a formal public participation. For the planning decision procedure, § 4 (2) EnWG refers to the respective provisions for energy gas pipelines in the EnWG and to the general planning decision regime in the VwVfG. Thus, although these references are in some details rather obscure, creating unnecessary legal uncertainty [BEN20b], the planning decision regime for CO_2 pipelines is in general aligned with energy gas pipelines, including the possibility to start the actual construction before the planning decision pursuant to § 4 (3) sentence 1 KSpG in connection with § 44c EnWG. But the CO_2 regime puts greater emphasis on early public participation: § 4 (1) KSpG pushes for a public participation even before the application of the plan is actually filed and a public dialogue (see in contrast § 25 (3) VwVfG as general stipulation for early public participation); certain provisions of the general planning decision regime to accelerate the procedure are not referred to. Especially, pursuant to § 4 (2) sentence 2 KSpG in connection with § 11 (2) KSpG, a procedurally simplified planning decision without prior public participation is only possible in the case of (essential) changes of existing CO_2 pipelines while in general (see § 74 (6) VwVfG) – given the respective and rather strict requirements – even the construction of new infrastructure projects can be subject to a planning decision without public participation.

Possible **environmental impact assessments** are integrated into the planning decision procedure. The size thresholds for unconditional environmental impact assessments and preliminary assessments of CO_2 pipelines pursuant to no. 19.10 Annex I UVPG are parallel to those for liquefied gas pursuant to no. 19.4 Annex I UVPG (and water-pollutants pursuant to no. 19.3 Annex I UVPG) and somewhat stricter than those for natural gas pursuant to no. 19.2 Annex I UVPG. For CO_2 pipelines with a diameter of more than 150 mm, at least a preliminary assessment is needed; this threshold will cover most if not any expected CO_2 pipelines for CCS (see section 2.2.1). Like for all pipeline projects, for CO_2 pipelines with a diameter of more than 800 mm and a length of more than 40 km, a full environmental impact assessment is demanded regardless of the specific circumstances; this threshold may cover main pipelines like a potential pipeline from Germany to the Netherlands (see section 2.2.1).

The **competent authority** for the permitting procedure is designated by the federal states, the Länder. The approaches for the designation of competences can differ greatly. For example, in North Rhine-Westphalia the general district authorities (the Bezirksregierungen) are competent pursuant to the general allocation of competence pursuant to § 8 (3) State Organisation Act (LOG NRW), while in Lower Saxony, another Land next to the Netherlands, the competence for most issues connected to the KSpG, including any issues related to CO_2 pipelines, is concentrated at the state office for mining, energy and geology (Landesamt für Bergbau, Energie und Geologie – LBEG), no. 12.3 Annex Environmental and Occupational Safety Competence Ordinance (ZustVO-Umwelt-Arbeitsschutz).

For **transboundary CO_2 pipelines**, article 24 CCS-Directive provides that the national authorities have to cooperate to safeguard the requirements of the CCS-Directive and other EU law [MAH20]. This provision was not directly transposed in the KSpG. Anyways, article 24 CCS-Directive has direct effect on the respective authorities. Moreover, §§ 54–59 UVPG in regard to transboundary environmental impacts provide a framework for transboundary cooperation of the competent authorities. Thus, for transboundary CO_2 pipelines, the cooperation of the different national authorities is warranted. However, they have to coordinate their cooperation without substantial legislative guidance.

Pursuant to § 15 Regional Planning Act (ROG), a preliminary (spatial) **regional planning procedure** for projects that are regionally significant can be foreseen. In a regional planning procedure, the compatibility of the project with regional planning is examined. The relevant federal ordinance on the matter, the Regional Planning Ordinance (RoV), does not provide for a regional planning procedure for CO_2 pipelines. But the law of the Länder can deviate from that; e.g., in North-Rhine Westphalia, a regional planning procedure for CO_2 pipelines with a diameter of more than 300 mm can be ordered on a case-by-case basis pursuant to § 43 (1) no. 2 lit. c) Ordinance to Implement the Planning Act of North-Rhine Westphalia (LPlG DVO).

In regard to the permitting procedure for CO_2 pipelines, the probably most pressing issue is the **duration of the procedure**, which is shaped by the legal framework, in the context of the timeliness of the completion of potential new pipelines. Three phases can be identified which dominate the duration from the first plan of a CO_2 pipeline to its actual completion: (1.) In the planning phase the pathway and technical specification of the pipeline are designed and the planners document that the designed pipeline meets the legal requirements to produce an application of the plan while the dialogue with the public commences. (2.) The actual permitting phase starts with the application for the planning decision at the competent authority, is governed by the review of the plan by the competent authority in regard of the legal requirements and ends with the planning decision. (3.) In the judicial review phase the planning decision can be challenged before court, especially if the competent authority granted the permission and third parties want to nullify or modify it; while pursuant to § 80 (2) sentence 1 no. 3 Administrative Court Procedure Code (VwGO) in connection with § 4 (2) sentence 1 KSpG in connection with § 43e (1) sentence 1 EnWG the judicial review does not bar the start of actual construction, an ongoing process can create uncertainties and hinder investments. All three phases inform each other and are therefore closely connected: The plan as a result of the planning phase is subject to the review during the permitting phase and the final planning decision, and the planning decision on this plan is subject to the judicial review. Accordingly, the competent authority and the applying planner will shape the permitting phase and the final planning decision in a way that it stands up to the judicial review while the planner will shape the planning phase in a way that the permitting procedure and the judicial review will produce the desired permission of the plan in a smooth way.

Lengthy procedures are an issue for any greater infrastructure project in Germany, yet this observation is especially true in regard to CO_2 pipelines. Although the special focus on public participation and according provision in the KSpG can have a delaying effect on the permitting procedure, this aspect does dominate the duration of the permitting procedure: The early public participation can be integrated into the planning phase with no or little loss of time and the differences to the energy gas pipeline procedure do not touch the general core of the procedure. Much more prominent drivers of presumably long procedures are the lack of experience of all involved actors with CO_2 pipelines, the lack of established technical rules and the remaining scientific and technical uncertainties in regard to CO_2 pipelines (see above section 4.1.2.1). In the planning phase, the planners cannot rely on their experience with natural gas pipelines or other established pipelines to guide the design of the pipeline. Nor can they focus on fulfilling established technical rules. Rather, they must settle technical challenges without or with little precedence, cope with remaining uncertainties and document with considerable effort that their solutions meet the safety requirements and are state of the art. At the same time, they have to observe the extensive research on CO_2 pipelines and, since there is no established administrative practice, they cannot predict whether the permitting authority will accept their plans. In the permitting phase, the competent authorities, also lacking experience and established technical rules, have to check the plan and the extensive documentation to validate the safety of the design to test the legal safety requirements. Since there are still uncertainties in regard to CO_2 pipelines, the competent authority may easily disagree with the position of the planners. If an authority comes to another assessment of the completeness of the documentation or the required safety of the planned pipeline, the planners have to restart planning and documenting, the results of which have to be checked and tested again by the authority. Even if new research and experience eliminate present uncertainties, the planners and the authority officials have to learn about this progress and be convinced of its significance. Additionally, the current developments in the technical and scientific discussion on CO_2 pipelines can impede and therefore slow the discussion between authority officials and planners. In the meantime, other interested parties, which are integrated into the public participation (especially land owners, local action groups and environmental organisations), have to be taken into account. They can also be unsettled and confused by the complex and new technical and scientific background. Due to this situation, communication between planners, authority officials and third parties can be time-consuming and prone to misunderstandings. Furthermore, due to the remaining uncertainties, the third parties can come to different conclusions in regard to the safety of the planned pipeline. These circumstances and the ambivalent perception of CCS in general (see section 5.6) add up to a high potential of conflict and thus likely litigation and judicial review. For the judicial procedure, the lawyers and judges – and also with not precedence – have to familiarise with the complex technical and scientific background as well as with the extensive documentation for the plan and the issues raised by the claimants. Although the litigation itself in principal does not hinder the start of constructions, the specific uncertainties connected to CO_2 pipelines increase the risk that a court comes to a different assessment of core aspects of the legality of the planned pipelines or that it sees mistakes in the process of the planning decision and therefore nullifies it. This risk undermines the planning security and the security of investment.

However, the options for **accelerating the planning procedure** are limited. The earlier a permitting procedure is started, the more it is affected by uncertainties and lacking experience. The more experience and certainty is secured before the start of the permitting procedure, the later it will produce the desired construction permit. Prompt and determined research and standardisation is essential to create a common and secure ground for permitting procedures but cannot be accelerated at will. Yet, there are also potential measures that are connected more closely to the procedure itself and its legal background. Aligning the procedural provisions for CO_2 pipelines with those for energy gas pipelines might help to accelerate the procedure. Moreover, this aspect is closely connected to the debate on accelerating permitting procedures for infrastructure projects in general. But since the main driver for this specific issue for CO_2 pipelines are uncertainties and a lack of experience and knowledge, the effect of these measure will probably be limited. Additionally, changing the procedural framework may also have negative effects, especially if it reduces public participation or judicial review, and should not be done without careful consideration. Adjusting the procedural framework to facilitate the building and dissemination of experience seem to be more effective and less problematic. For example, the competence for CO_2 pipelines could be concentrated at single authorities within the different Länder as in Lower Saxony or, less incisive to the administrative organisation, a centralized consultation body could be formed. Also the concept of project managers pursuant to § 43e EnWG could be expanded to CO_2 pipelines, perhaps even expanding also its role [BEN20b]. Project managers are private entities that support the competent authorities with certain tasks of the permitting procedure, especially in regard to the coordination of public participation and the quality control of the documentation provided by the planners. In the context of CO_2 pipelines, they could quickly build up expertise and offer it to competent authorities in different Länder, especially if these do not have their own experience with CO_2 pipelines and/or inadequate resources. Even more important than these legal adjustments are actual measures in regard to permitting procedures for CO_2 pipelines, which have to be taken by governments and officials: e.g., training on CO_2 pipelines to build up knowledge within the administration, cooperation of different authorities to disseminate knowledge and experience, guidelines to create a common ground for discussion, the allocation of resources to enable swift permitting procedures.

Additionally, a strategic development of the pipeline network can take the creation of knowledge and experience into account: A first pipeline section can be planned and constructed, perhaps with public support to account for the special risks and the public benefits and even under the umbrella of a PCI (pursuant to the TEN-E Regulation), to create precedence for planners, authority officials, interested third parties and courts in a clear and manageable environment.

The legal framework of the permitting procedure for CO_2 pipelines is, although it shows some peculiarities, close to the permitting procedure for energy gas pipelines. There are some minor and easily removable inconsistencies, but no major legal hurdles. Due to the technical and scientific uncertainties as well as the lack of experience and established rules in regard to CO_2 pipelines, the actual permitting procedures will take much more effort and time than the already rather complex and lengthy permitting procedures for energy gas pipelines. While there are some options for legislative measures that might help to accelerate the procedures, it will probably be more effective to directly target the actual lack of knowledge and experience, highlighting the critical role of research and training in this area. These measures might be able to mitigate the lengthiness of the procedures, but will not remove this major issue.

4.1.2.3 Expropriations

Pursuant to § 4 (5) KSpG, expropriations for CO_2 pipelines are possible if they are necessary for the realisation of the pipeline and if the pipeline serves the public good. In the case of storage abroad, the CO_2 pipeline serves the public good if the emission of CO_2 in Germany can be permanently reduced in this way; thus, pipelines for the transit of CO_2 from another country to a third country do not allow for expropriations. Whether these requirements are met, is determined in the planning decision. This decision is binding for the actual expropriation procedure, which is regulated by the Länder, see §§ 4 (5) sentence 5, 15 (3) KSpG. Additionally, an expropriation is only possible if it was tried to buy the respective property beforehand, §§ 4 (5) sentence 5, 15 (2) KSpG. Furthermore, § 4 (3) sentence 1 KSpG refers to the accompanying stipulations of §§ 44a, 44b EnWG to facilitate expropriations. There are no further details by an ordinance pursuant to § 4 (6) no. 1 KSpG.

The expropriation regime for CO_2 pipelines from Germany to the Netherlands is parallel to the expropriation regime for energy gas pipelines and rather favourable.

4.1.3 Operation

The operation of CO_2 pipelines is highly shaped by its legal framework, that touches a multitude of legal aspects: The market regulation (third party access, tariffs regulation) governs the behaviour of the operators towards its customers in the context of natural monopolies; damages due to accidents during the operation are covered by the liability regime, while the major accidents regime aims at the prevention of and quick response to accidents; system responsibility of the operators creates the legal framework in regard to the quality of the CO_2 stream.

The **market regulation** regime for CO_2 pipelines can be found in § 33 KSpG and is supplemented by general competition law. Pursuant to § 33 (1) KSpG, operators have to grant third parties access to CO_2 pipelines. The conditions for the access (including tariffs) have to be non-discriminatory, technically and economically feasible and transparent. Pursuant to § 33 (2) KSpG, which implements article 21 CCS Directive, third party access can only be denied by the operator if strict requirements are met: Granting the access have to be impossible or unbearable due to limited capacities or legal requirements. The competent authority for enforcing this market regulation – notwithstanding the competence of the general competition authorities – is the Federal Network Regulation Authority (Bundesnetzagentur – BNetzA). Further specific market regulation is not given. Although § 33 (4) KSpG empowers the Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie – BMWi) to enact ordinances to provide further specifications for third party access, this power was never used.

Pursuant to § 29 KSpG, which covers all CCS related sites within the scope of the application of the KSpG, operators have to pay **damages** if the operation of the pipelines causes the death of a person, damages to health or damages to assets. The causality of the operation for the damage is assumed if the operation is likely to have caused the damage under the specific circumstances of the case, unless the pipeline was operated as intended and a likely alternative cause can be proven. This liability regime is – in regard to the needed prove of likely alternatives – stricter than comparable regimes for pipelines and rather aims at underground storage operations. It is questionable whether the special assumption will ever be triggered for pipelines, but nonetheless the current liability regime for CO_2 pipelines creates risks of liability for CO_2 pipeline operators that are unnecessary and contrary to the general structure of liabilities [BEN20b].

Pursuant to § 4 (3) sentence 2 KSpG in connection with § 49 (1) EnWG, CO_2 pipelines have to be operated safely. Therefore, operators have the duty to prevent **major accidents** and to mitigate possible damages in the case of a major accident. Furthermore, § 4 (6) no. 2 KSpG empowers the BMWi to enact ordinances of the safe operation of CO_2 pipelines. Therefore, the KSpG creates a special major accidents regime for CO_2 pipelines, which displaces the general major accidents regime for pipelines of the Transport Pipeline Ordinance (RohrFLtgV). However, a respective ordinance for CO_2 pipelines has not been enacted yet. Thus, there are no operative duties for the operators, especially in regard to the interaction with the competent authority, beyond the general requirement of safe operation. Although this situation is in line with EU law – especially, the CCS Directive requires special duties only in regard to leakages of the storage site, see articles 16, 3 no. 5 –, it is unsatisfactory both in regard to safety and in regard to clear guidelines for the operators. Before the operation of CO_2 pipelines starts, the BMWi needs to produce an ordinance for a detailed major accident regime which can be based on the existing regimes of the general RohrFLtgV and of the High Pressure Gas Pipeline Ordinance (GasHDrLtgV) for energy gas pipelines [BEN20b].

The pipeline operators are responsible to safeguard the **quality of the CO_2 stream** in their pipeline. They have to take care, that impurities in the stream – or their interaction – do not impair the safety of the pipelines or of downstream pipelines and storage sites. In an international network of CO_2 pipelines that collects CO_2 from a multitude of different sources with different impurities, a coordination between different operators and customers is needed to do so [BEN20b; BEN20d]. Neither at national [BEN20d] nor at EU level [BEN20d; MAH20], the relevant legislation provides any coordination mechanism. Rather, the third party access regime even hinders a voluntary coordination [MAH20]: Pursuant to article 21 (2) lit. d) CCS Directive, member states may also consider reasonable needs of the owner or operator and the interests of all other users of the network or relevant processing or handling facilities who may be affected when allowing operators to refuse third party access. This provision can be used to enable some margin for CO_2 stream coordination and a strategic development of stream requirements in a growing network, but it remains rather vague; in Germany, the KSpG does not implement this option anyway. To facilitate the coordination of CO_2 streams, which is essential for international CO_2 transportation networks for CCS, a development of the legal framework in the EU and in Germany is necessary before the begin of widespread pipeline operation: The new framework has to give clear guidelines for the operators, enable an effective coordination and remove respective hurdles.

The legal framework for CO_2 pipeline operation in Germany in its present form does not suit the actual needs: The liability regime does not fit pipelines operations and adds unnecessary – albeit limited – financial risks for the pipeline operators. The major accidents regime needs further *details by a respective ordinance. Most notably, the current legal framework rather hinders than facilitates an effective coordination mechanism for CO_2 streams in a pipeline network. The later issue also requires actions at EU level.*

4.1.4 Export and Market

In regard to export, CO_2 for CCS is considered waste. Pursuant to the Shipments of Waste Regulation, shipment restrictions due to international agreements have to be observed (see article 11 (1) lit. f) for shipments between Member States). For Germany, which is party to the **London Protocol**, the export of CO_2 for offshore CCS is therefore prohibited [BEN20b]. Yet, since the parties of the London Protocol agreed on the possibility of the provisional application of the 2009 amendment, which was meant to soften the export prohibition for CO_2 but never came into effect [HEN17], in 2019 [BAN19], this restriction can be removed. Now, to enable the export of CO_2 from Germany for offshore CCS in the Netherlands, Germany and the Netherlands have to declare the provisional application of the 2009 amendment and negotiate a respective agreement.
Under the current system, the main economic incentive for CCS is the reduction of the need for allowances for CO_2 emission in the **EU ETS**. Since the EU ETS Directive at EU level and the (implementing) TEHG in Germany also cover the pipeline transportation of CO_2, there is no legal hurdle in this regard. The National Fuel Emission Trading Act (BEHG), which covers most CO_2 emissions outside of the EU ETS, does not include any reference to CCS. Yet, this omission is not a relevant issue since the BEHG typically covers activities (heating, transportation), for which CCS is not feasible anyway. A relevant legal issue in regard to the integration of CO_2 transportation into the EU ETS is the role of transportation by other means than pipelines, especially ships: Neither the EU ETS Directive nor the TEHG refer to other means of transportation, which creates legal uncertainty in regard to consequences of deploying such means in the CCS chain [RYD15]. While this uncertainty does not directly affect CO_2 pipelines and rather gives them a comparative advantage as a means of CO_2 transportation, it impedes the creation of an efficient CO_2 transportation network with different, needs-based transportation options as a whole.

CO_2 pipelines are integrated into the EU ETS and therefore legally incentivized. While the export of CO_2 for offshore is still prohibited due to the London Protocol, this prohibition can be removed when Germany and the Netherlands agree so and declare the now possible provisional application of the 2009 amendment to the London Protocol. To facilitate the development of an efficient CO_2 transportation network further, the place of all relevant means of CO_2 transportation in the EU ETS, especially by ship, has to be clarified.

4.1.5 Assessment of Risks and Opportunities

The legal framework for CO_2 pipelines in Germany is in many ways insufficient and displays a number of legal hurdles. Yet, these deficiencies can be overcome without intensive intervention into the legal landscape or major social conflict.
The construction regime of the KSpG is sufficient to start the planning of CO_2 pipelines. However, more substantial steps will need further technical research and legal developments. Especially, the legal framework for the operation of CO_2 pipelines is in need for adjustments and operational details: e.g., details in regard to major accidents, the provisional application of the 2009 amendment to London Protocol to allow CO_2 export for offshore CCS, the role of CO_2 ship transportation in the EU ETS, coordination of CO_2 streams from multiple sources. Some of these developments also involve the EU legislator (EU ETS, CO_2 stream coordination). Since these developments address rather regulatory details than substantial political decision – even the

provisional application of the 2009 amendment would rather confirm the general endorsement of CO_2 export by the KSpG and would not create any immediate effects –, they are connected to no or little regret. Yet, the actual effort for these developments varies from simple political decision (London Protocol, EU ETS and ships) to unprecedented and detailed mechanisms in a complex environment (CO_2 stream coordination). Anyway, the new legal regime for pipeline operations does not have to be in place before actual operations are foreseeable. However, the discussion on it has to begin now and guiding principles have to be determined early enough to inform the respective investment decisions.

The main issue in the legal context of CO_2 pipelines is the long duration of the permitting procedure due to the generally long permitting procedure, technical and scientific uncertainties and the lack of experience with CO_2 pipelines. There are measures that might be able to mitigate the duration, some of which are no or low regret (e.g., trainings, extension of project managers and other proven modernisation of the planning decision procedure to CO_2 pipelines) while others are intense interventions into the current regime (e.g., public participation). Nevertheless, the permitting procedure will take a long time anyway. Therefore, taking into account that concrete investment decision for CO_2 pipelines in Germany cannot be foreseen in the near future, it cannot be expected that an extensive CO_2 pipeline network in Germany can be operational in 2035. At most, the completion of single pipelines seems feasible in this timeframe. At the same time, this situation stresses the need to start substantial discussions and take first actions soon, since otherwise valuable options to mitigate greenhouse gas emissions may be lost in the long run.

From a legal point of view, to establish a CO_2 transportation network, the ambition should not aim at an extensive pipeline network by 2035. Rather it should focus on single relevant CO_2 pipelines which can be complemented by ship transport. Further pipelines can be planned, permitted and constructed on the base of the respective experiences and the general development of CCS. Given the duration of the permitting procedure and the construction of CO_2 pipelines, the extension of the rudimentary network has to be planned well before the completion of the later in a dynamic learning process, while ships can expand this network flexibly along the shipping ways.

- For this purpose, as an **immediate action**, a substantial discussion on the political goals and the legal technicalities has to commence in the EU and in Germany. Actors of this discussion have to be scholars and practitioners from business, administration and politics. A strong political signal that CCS in the context of CO_2 transportation networks is on the agenda (without necessarily already committing to CCS) can ignite such a discussion. In the EU, the identification of CCS projects as PCIs in the context of the TEN-E Regulation constitutes such a signal; the extension of the EU ETS to ships and other means of transportation would give this signal even more credibility. In Germany, addressing legal inconsistencies in regard to CO_2 transportation (e.g., liability regime, unclear references) is a low hanging fruit to give a noticeable signal without committing to a certain CCS policy. A much more powerful signal without commitment in the matter would be the declaration of the provisional application of the 2009 amendment to the London Protocol.
- At an **early stage**, this discussion should lead to the planning and permitting of first CO_2 pipelines as a showcase. This showcase has to be backed by the relevant industry actors (pipeline operator, storage site, CO_2 emitters) and by the public hand, which has to take legislative and material measures to disseminate the experience from this showcase. Based on the ongoing experiences from the showcase and the substantial discussion, a political commitment on the goals of the CCS policy and on the principles of the CO_2 pipeline operation regime is needed to inform further investment decisions.
- **In the long run**, well before the actual start of the operation of the first CO_2 pipelines, a fully operational and detailed pipeline operation regime is needed. Until then, there is still a lot of time left. However, since the creation of such a regime is a very challenging task,

this time should be used well. Additionally, to allow the transit of CO_2 through Germany in a European CO_2 network (e.g., from Switzerland) without creating legal uncertainties, expropriations should be made possible for CO_2 transit pipelines as well.

4.2 Base Option 2: Blending H_2 in Natural Gas Transmission Pipelines

4.2.1 Legal Background

The blending of H_2 into the natural gas grid is governed by the extensive **natural gas pipeline regime** of the EU – especially Directive 2009/73/EC (Natural Gas Directive) and Regulation (EC) 715/2009 (Natural Gas Transmission Network Regulation) – and of the EnWG and associated ordinances, which implement the Natural Gas Directive and supplements the Natural Gas Transmission Network Regulation. There are some provisions that explicitly refer to H_2 injection, which focus on power-to-gas contexts.

Most notably, § 3 no. 19a EnWG defines H_2 that was produced by electrolysis (and is injected into the gas system) as gas. Whether the **gas definition** is exclusive and therefore excludes H_2 produced in other ways [BUN20b; KAL19] or it is open for comparable gases like blue hydrogen [BEN20a], is open to debate, especially since the definition was never meant to discriminate different forms of H_2 production and an exclusive definition would infringe the Natural Gas Directive, see article 1 (2) [BRA19; RON20]. Nevertheless, the consequences of this legal uncertainty are limited: The injection of legal non-gases is not prohibited as long as it is safe; and the applicable law for dedicated H_2 pipelines is an independent discussion (see section 4.3.1). The consequences of excluding other kinds of H_2 from the gas definition are restricted to the non-application of the EnWG rules for injecting the respective gas, especially the rules on third party access, tariffs and non-discrimination. Moreover, even these legal consequences would have little effect since general competition law would than fill the gap and there is little incentive for the pipeline operators to treat other gases differently than the EnWG-regulated gases. Anyways, clarifying the gas definition to encompass all sorts of H_2 would be helpful [BEN20a; BRA19; KAL19; RON20; ROS20]; to restructure the definition in a more open way – parallel to the scope of the Natural Gas Directive – is a suitable solution.

A more profound problem of the H_2 injection regime than the legal uncertainty in regard to blue hydrogen is the **general aim of the regime**. While the injection of green hydrogen as renewable gas is generally privileged, the regime as a whole rather limits the injection of H_2 to prevent the impairment of the natural gas system. A substantial increase of the share of H_2 is not foreseen in the current framework and therefore impeded.

For the injection of H_2 into the natural gas transmission system, the natural gas regime of the EnWG and associated legal provisions is applicable. However, the current natural gas regime aims solely at the stability of the natural gas system and does not address the specific challenges and conflicts of substantially increased shares of H_2 in the system. Additionally, there is some legal uncertainty in regard to the gas definition and H_2 produced from natural gas.

4.2.2 Construction and Change of Operation

The specific **safety requirements** for the construction of natural gas pipelines and auxiliary facilities are governed by § 49 EnWG (with further details in the GasHDrLtgV) [BEN20c]: The facilities have to be constructed in a safe, state of the art way. Since the property of the gas changes when more H_2 is injected, some components in the natural gas system might have to be adjusted or exchanged to transport more H_2 safely [WAC19]. The relevant standardisation body in Germany, the DVGW, is currently working to update its standards for natural gas pipelines in regard to higher shares of H_2. As far as such standards are not available yet, the legal facilitation for the planners pursuant to § 49 (2) EnWG concerning the requirements and their documentation (when the respective standards are observed) is not available; planners will have to prove and document the safety of the pipelines and facilities to the competent authorities.

The **adjustments to facilities** like compressor stations that are necessary to safely increase the share of H_2 in the gas system are usually rather limited [MÜL13] and, if not already covered by the existing permit, need a simple building permit by the local building authority [BEN20c]. Only adjustments with substantial impact on transmission pipelines and their operation might require planning decisions (see for planning decision procedures section 4.1.2.2). It is also possible to combine individual adjustments pursuant to § 43 (2) sentence 1 no. 1 EnWG with the (technical) permission to transport gas with an increased share of H_2 in the respective pipelines and get the complete change permitted by a planning decision [BEN20c]. The planning decision procedure is more complex and expensive, but it allows a comprehensive decision on all involved conflicts and getting permits before the actual switch to high H_2 shares.

The actual **increase of the share of H_2** needs a permitting procedure if it is not already covered by a permit (already existing permits for natural gas transmission pipelines will usually not cover the transport of a substantially higher share of H_2, regardless of the wording). Substantial changes on gas transmission pipelines have to be reported to the competent authority beforehand, see §§ 8, 5 GasHDrLtgV; since substantially higher shares of H_2 in natural gas pipelines have a different risk profile, this provision also addresses the increase of the share of H_2 [BEN20c]. Beyond this general requirement, the increase of H_2 in smaller pipelines demands simple permits similar to adjustments to facilities. For larger transmission pipelines with a diameter of more than 300 mm, the permission for the operational change has to be granted by a planning decision procedure according to § 43 EnWG. This procedure can entail an environmental impact assessment. In the case that an environmental impact assessment was already performed for the construction of the respective pipeline if the change can result in a relevant additional environmental impact, an environmental impact assessment is necessary for the increase of H_2, see § 9 (1) UVPG. The increase of H_2 will impact the respective system as a whole and – in connection with the changes of the risk profile due to the blending – a relevant additional risk for the immediate environment can hardly be ruled out without further examination. Thus, if an environmental impact assessment was conducted for a natural gas pipeline, the change of operation to substantially increase the share of H_2 in the pipeline will most likely demand a further environmental impact assessment. For the change of older (or environmentally less relevant) pipelines for which no environmental impact assessment was performed, a first environmental impact assessment will only be due if the change reaches a threshold for assessments for the first time, see § 9 (2) UVPG), or if no thresholds are foreseen, see § 9 (3) UVPG; for the mere change of operation in respect of the transported gas, this is not the case. Thus, for the increase of the share of H_2 in older (or less relevant) pipelines, an environmental impact assessment is not demanded. The competent authority may simplify the planning decision procedure pursuant to § 74 (6) VwVfG (no public participation) or to § 43f EnWG (the changes have to be reported beforehand but a permission is not needed) if – in a nutshell – other private and public interests are considered otherwise and an environmental impact assessment is not due. This means that these simplifications are not available for the operational change to substantially more H_2 if the respective pipeline was constructed with an environmental impact assessment. Therefore, the complex and cumbersome basic planning decision procedure with an integrated environmental impact assessment, which is designed for complex environmental interactions and weighing of interests, is applicable to the operational change in respect of the transported gas, although its potential environmental impacts are limited to distinct areas in the event of an unlikely major accident and to mere shifts in the risk profile (without necessarily increasing the overall risk). This situation is a mismatch. And since the permitting procedure will be applicable to the whole of the natural gas transmission system (as far as an environmental impact assessment was performed) at the same time, it is an actual hurdle for the uniform increase of the share of H_2.

To **remedy this procedural burden** of the extensive increase of H_2, a strategic scheduling of planning decision procedures can help [BEN20c] but will not solve the problem at its core. A substantial simplification of the procedures would have a more meaningful impact. In this context, it is discussed to apply § 43f (2) sentence 1 no. 1 EnWG to the change of the transported gas. The provision allows dispensing the environmental impact assessment and thus using the procedural simplifications if only the concept of operation is changed. However, it is clearly aimed at power lines and its application to gas pipelines is doubtable. Yet, for the legislator, it seems feasible and systematically in line – also with the EIA Directive – to create a preliminary procedure to examine the safety of the change of the transported gas and to allow doing without a full planning decision procedure if this examination does not reveal any relevant additional risks, parallel to or even extending § 43f (2) EnWG. From a practical perspective and in the light of acceleration, this procedure should be designated to the competent authority of the Länder, which already have experience in this field, rather than to a new federal authority, which would have to be created, or to an existing federal authority (like the BNetzA), which has no experience with the safety of gas pipelines.

The **competent authority** for the planning decision procedure is determined by the Länder and may differ: E.g., in North-Rhine Westphalia the general district authorities are competent pursuant to § 1 (2) Ordinance to Desginate the Competences in the Area of Energy Industry (Verordnung zur Regelung von Zuständigkeiten auf dem Gebiet des Energiewirtschaftsrechts) and in Lower Saxony the single competent authority is the LBEG pursuant to no. 11.1.2 Annex ZustVO-Umwelt-Arbeitsschutz, parallel to the construction permits for CO_2 pipelines.

Under the current tariffs regulation regime for natural gas systems in Germany, the **additional costs** for adjusting the grid to increased shares of H_2 are not foreseen and reduce the possible revenue of transmission system operators (TSOs), which is an obstacle for respective investments [BEN20c; BUN20b]. To remove this obstacle and pass on the costs to the customers, different approaches within the system of incentive regulation are viable, e.g., by expanding the possible costs that can be directly passed on without comparison with other system operators or by demanding adjustments from all system operators, which eliminates the relative inefficiency of the adjustment costs and therefore allows their passing-on [BEN20c]. However, all of these approaches demand a legislative intervention (amendments to the relevant ordinances will not suffice). If the passing on of the costs to natural gas transport customers is enabled, the relation between the natural gas system and a dedicated H_2 system in regard to repurposed pipelines and cross-subsidies has to be considered (see below section 4.3.2.4). The additional costs can also be covered outside of the tariffs regulation regime: A general passing on mechanism could emphasize the responsibility of all gas customers to decarbonize the transport of gas [SAD18] without allowing cross-subsidies for individual TSOs [BEN20c]; direct subsidies for adjustments measures acknowledge the decarbonisation of the current gas system as a national effort but have to comply with EU law [SIE20]. The sooner the funding for adjustments is secured and the adjustments can start, the less the adjustments will cost (renovation cycles) [MÜL18].

Since the injection of H_2 into the natural gas system does not touch the status of the respective pipelines and facilities as part of the natural gas grid, the adjustments have no effect in regard to the **expropriations** for the respective pipelines. Only when the increased share of H_2 becomes dominant within the pipeline, questions may arise that are similar to the situation of repurposing existing natural gas pipelines to dedicated H_2 pipelines (see section 4.3.2.3).

The necessary adjustments of the gas system to increased shares of H_2 in regard to the construction are rather limited and spark little legal obstacles. In respect of the safety *requirement, the lack of established rules and standards has to be observed and increases the burden of safety documentation. Permitting procedures are dominated by simple building permits, but it is possible to integrate individual adjustments into an overarching planning decision procedure. The actual operational change in respect of the transported gas will likely demand a planning decision procedure with an environmental impact assessment for larger transmission pipelines; legislative changes could allow clear simplifications of the procedure. The system operators bear the extra costs of adjustments and may not pass them on to transport customers; to allow passing-on the costs, the legal environment has to be changed.*

4.2.3 Operation

System operators have the duty to ensure the gas quality in their system in respect of applications, safety and interoperability as part of their **system responsibility**. According to the common understanding of this duty, TSOs are not allowed to unilaterally change the operation of their pipelines to increase the share of H_2 substantially [BEN20c] (at least unless they are able to control and reduce the share of H_2 at the respective positions in the grid). Rather, a substantial increase of H_2 at transmission level will require a cross-network coordination, which – since the German transmission pipelines are heavily integrated into the European gas grid – has to be embedded in a European effort [BEN20c; PET18; WAC19]. Furthermore, due to the legitimate expectations of transport customers and the plethora of possible conflicts, the coordinated shift to increased shares of H_2 most likely has to be accompanied by a corresponding legal framework [BEN20c; WAC19]. The situation is quite different for distribution systems since they are less interconnected and individual distribution systems may lack particularly demanding customers; especially in small networks, the operators may be allowed to increase the H_2 share unilaterally or with only little coordination.

If the increase of H_2 shares can be coordinated, the operation of the natural gas system is still rather challenging from a legal point of view. A relevant H_2 injection has to be integrated into the natural gas market regulation and the network development plans (NDPs), raises safety issues and requires a new approach to the gas quality management.

In principal, the natural gas **market regulation** for transmission network operation, which also applies for H_2 injections, is a proven legal framework. Yet, there is a specific issue in regard to the integration of blue hydrogen. The legal uncertainty in respect of the gas definition (see above section 4.2.1) has a specific impact on the market regulation: While blue hydrogen may be injected into natural gas system regardless of the interpretation of the definition, the application of market regulation stipulations, especially for third party access, depend on the interpretation of the gas definition. However, the effect of the legal uncertainty on third party access of blue hydrogen suppliers is limited: Outside of the natural gas market regulation, general competition law applies. And since in Germany most TSOs are part of a vertically integrated undertaking (as independent transmission operators) that also supplies gas, § 19 (2) no. 4 Act Against Restraints of Competition (GWB) would demand to grant blue hydrogen suppliers non-discriminatory access, regardless of the third party access regime of the EnWG. Additionally, the strict unbundling regime of the natural gas market regulation, which prohibits system operators to also produce and supply H_2 [BUN20b], have been viewed critically because a close coordination of supply and transport could facilitate the introduction of new technologies and an H_2 economy [BOR20]. However, these objections are voiced rather in the context of power-to-gas and sector integration, while blue hydrogen is much closer to the traditional supply chain of natural gas.

The **strategic planning** of the natural gas system is governed by ten years NDPs for gas, which are developed by the TSOs based on the scenario framework (with assumptions on demand, supply and transportation needs) every second year and approved by the BNetzA. Since H_2 injection is relevant for the natural gas system, it is also considered for the NDPs for gas. Yet, the BNetzA is rather reluctant to integrate assumptions on H_2 into the NDP and essentially demands its discussion in a separate model outside of the base model ("Grüngasvariante"); the perspectives on H_2 production are considered too vague for further consideration and integration [BUN19; GRÖ20]. This position is consequent from the perspective of network development planning but also entails the risk to hinder further developments in H_2 blending: While H_2 injection cannot be fully considered in the NDPs due to a lack of concrete plans, concrete plans on H_2 injection are impeded without full integration of H_2 into the NDPs. Only time and experience will show, whether the BNetzA and the TSOs will find a workable arrangement on H_2 planning (in connection with other instruments to foster H_2 projects) or legislative intervention is needed to address the specific issues of large scale H_2 injections, especially in respect of the lack of concreteness of long term planning in a dramatically changing environment. The EU Commission is planning to integrate H_2 into NDPs [EUR20].

Pursuant to § 49 (1) EnWG, the **safety of the operation** of natural gas systems – next to its construction – has to be provided. The GasHDrLtgV adds further details, especially concerning the prevention and reporting of major accidents. Since the quality of natural gas with high H_2 admixture differs from natural gas as used today, the substantial injection of H_2 can require adjustments to the management and operation of the pipelines and its auxiliary facilities, e.g. in regard to the pressure management [KRI12]. Anyways, as long as existing permits do not already include higher shares of H_2, the change in operation by blending substantially more H_2 in the system, requires a permit by the competent authority, which has to check the safety of the new operation parameters [BEN20c]. For larger transmission pipelines (with a diameter of more than 300 mm), this permit requires a planning decision pursuant to § 43 (1) sentence 1 no. 5 EnWG.

With increased H_2 shares, the management of the **gas quality** becomes a new challenge that demands an appropriate legal framework. In a system with a blend of H_2 and methane from different sources, it does not suffice to ensure the injection of a uniform quality of gas (as with L- and H-gas). Rather the injection of the different gases has to be coordinated to safeguard that the mixture in the system meets the overall requirements of the system. Additionally, the cross-border interoperability of the natural gas systems has to be safeguarded, which calls for the reinforcement of the existing coordination mechanisms [EUR20]. These challenges are even more pressing if a constant share of H_2 is necessary to satisfy the demands of the gas customers. Under these circumstances, the legal framework has to allocate responsibilities and costs for coordination, strengthen the supervision by the competent authorities and provide for damages and liabilities. Most likely, in a system with substantially increased shares of H_2, the TSOs will have a new and much more critical role.

Under the current law and in the current situation, individual TSOs may not allow a substantial increase of the share of H_2 in the natural gas transmissions system. For this purpose, a high level coordination is needed, which encompasses all levels of the natural gas system, considers the neighbouring countries in the EU and probably needs legislative support. The substantial increase of H_2 demands adjustments in the management of the pipeline operation. Partly, the legal framework covers these adjustments, such as for the safety of the pipeline operation. Partly, it sports deficiencies that have only limited effect, such as for the legal uncertainty in regard to the application of market regulation rules to blue hydrogen, or might be compensated by cooperation of the stakeholders, such as for the role of H_2 in the NDPs. And partly, substantial legislative interventions will be necessary, especially in regard to the management of the gas quality, which will heavily impact the structure of the stakeholders in the gas market, especially the role of TSOs.

4.2.4 Market

In the context of the injection of H_2 into the natural gas transmission system, four legal issues that are relevant for the H_2 market have been identified: privileges for green gas, guarantees of origin for blue hydrogen, the integration of blue hydrogen in CO_2 pricing mechanisms and accounting.

There are **privileges for green gas** including green hydrogen [BRA19], especially priority injection pursuant to § 34 Gas Network Access Ordinance (GasNZV), which do not extend to blue hydrogen. This situation limits the capacities for the injection of blue hydrogen, which may not displace (potential) green hydrogen in respect of the maximum amount of H_2 in the system. While the priority of green hydrogen relative to blue hydrogen could be removed by amending the respective ordinance, this measure would be contrary to the current national H_2 strategy that prioritizes green hydrogen [BUN20a] and might be questionable in respect of the acceptance of H_2 injection (see section 5.4).

Another overarching legal issue of the H_2 market is the certification of clean and low-carbon H_2 [EUR20]. At EU level, Directive (EU) 2018/2001 (RED II Directive) foresees **guarantees of origin** for renewable gases, including green hydrogen [ROS20]. For blue hydrogen, no guarantees of origin are stipulated in Germany, neither at EU level nor at national level. This omission is in line with the current system, which fosters renewable energy (and efficiency) and relies on technologically neutral CO_2 pricing otherwise to combat climate change. There are private initiatives to certify different kinds of H_2 with a mitigated climate impact [BUC19]. It is also discussed to introduce public guarantees of origin in respect of blue hydrogen to support a differentiated cross-border marketing of H_2 in connection with CO_2 mitigation [ACE19].

The current **CO_2 pricing** mechanisms cause a competitive disadvantage of blue hydrogen relative to natural gas. Pursuant to the EU ETS, blue hydrogen demands greenhouse gas allowances for its production while allowances are only needed for specific uses of natural gas; therefore, for certain uses, especially heating, the use of blue hydrogen demands allowances under the EU ETS while the use of natural gas does not – despite the actual mitigation of CO_2 emissions [BEN20d]. The national CO_2 pricing mechanism for CO_2 emissions outside of the EU ETS scope pursuant to the BEHG mitigates this disadvantage. But a disadvantage remains and, depending on the price for allowances in the EU ETS and the effectiveness of the CO_2 emission reduction in the production of blue hydrogen, the CO_2 price for low-carbon blue hydrogen can (at least in theory) still be higher than for full-carbon natural gas. An additional issue in the context of CO_2 pricing is the allocation of costs for the CO_2 emission reduction: Since the use of H_2 does not create CO2 emissions, a higher amount of H_2 in the natural gas networks will reduce the need for allowances; and because all customers of the network use the same blend, all customers directly profit from this reduction, no matter where they purchased the gas. Under the current system, the mitigation measures at the site of the production of the blue hydrogen cannot be attributed to the actual reduction of the need of allowances on the side of usage; despite its purpose, the EU ETS does not give any tradable incentive to mitigate the emission of greenhouse gases [BEN20d]. The distortions can be removed by changing the architecture of the CO_2 pricing mechanisms. Moreover, the distortions are irrelevant if a fixed quota of H_2 (either on supplier level or on transport level) is established: Since H_2 and natural gas do not compete in such a system, the relative distortions have no effect.

Since H_2 and natural gas have different values for gas customers, **accounting** can be problem in the case of a substantial admixture of H_2. Metering and quality control can be difficult and are accompanied by costs and possible damages, especially in a system of highly fluctuating gas quality. Furthermore, accounting cycles have to be adjusted to cover H_2 [KAL19]. The relevance and consequences of these accounting issues as well as possible ways to mitigate them are highly dependent on technical and regulatory details of the pathway to H_2 blending. Therefore, this aspect has not been examined further in the context of this project. The issues have to be researched further in the light of coming developments and specific concepts.

In the current legal situation, the integration of the German economy into an H_2*-CCS chain by increasing the share of* H_2 *in the natural gas system meets several legal issues in respect of the market situation. In a blended grid,* CO_2 *pricing mechanisms give* H_2 *a relative disadvantage in comparison to natural gas. Unlike for green hydrogen, there are no guarantees of origin for blue hydrogen. Additionally, the injection of blue hydrogen has to consider the priority of green hydrogen, which limits the quantity of blue hydrogen in the gas system. While the relative disadvantage in comparison to natural gas can be addressed in different challenging ways, the relative disadvantage in comparison to green hydrogen is in line with the political momentum and the overall goals of climate neutrality. To balance the legally created disadvantages of blue hydrogen in the market relative to natural gas, intensive interventions in the current legal framework (new* CO_2 *pricing mechanisms, fixed* H_2 *quotas) can help. The limitations in regard to green hydrogen rather have to be accepted.*

4.2.5 Assessment of Risks and Opportunities

Although a legal framework for the injection of H_2 into the natural gas system is provided, it is not fit to enable a substantial increase of the share of H_2 in the gas transmission system. On the one hand, a substantial increase is virtually forbidden, at least without an extensive and international coordination of the stakeholders (especially system operators and gas customers). This legal situation is in line with the need for coordination to establish a market for blended gas. On the other hand, a substantial increase of the share of H_2 produces regulatory needs, which are not properly addressed by the current legal framework: The increased challenges of gas quality management in a blended system is not reflected by corresponding stipulations, the permitting procedure for the actual increase of H_2 is unnecessarily cumbersome, H_2 and especially blue hydrogen are put into a relative disadvantage in comparison with natural gas, there are no satisfactory rules in respect of the costs of adjustments.

From a legal point of view, intensive interventions in the legal framework are needed – next to a close coordination of the relevant stakeholders on a European level – to enable a substantial increase of H_2 in the gas transmission system. These interventions will affect the role and structure of the different stakeholders, especially the TSOs, and will ultimately change the market structure for natural gas. Accordingly, the legislative interventions are connected to difficult issues and significant conflicts, especially in regard to the interests of different gas customers, the allocation of costs and new responsibilities and powers.

Additionally, green hydrogen is prioritized by the current legal framework (and the political momentum). Therefore, the effect that increasing the share of H_2 in the gas transmission system will have on the integration of blue hydrogen in the German economy is limited. In a blended gas system, blue hydrogen will rather have a supporting role.

Overall, with corresponding adjustments in the legal framework, it seams legally feasible to increase the share of H_2 in the gas transmission system. Yet, the necessary interventions are complex and demanding. In any way, this option does not emphasize the role of blue hydrogen. Whether the necessary changes can be materialized, depends on a number of unpredictable developments and policy choices with little connection to the discussion on blue hydrogen. Still, blue hydrogen can play a supporting role in this option if it is pursued.

The necessary legislative actions depend on the details of the implementation. Especially if the share of H_2 in the system is fixed, the lack of flexibility has to be observed and the need for coordination is substantial – probably with a new role for the TSOs –, but other issues like the relative marketing disadvantage of blue hydrogen do not need to be addressed anymore.

- To prepare a timely and substantial blending of H_2 in the gas transmission system, some **immediate actions** are necessary from the legal perspective. Recently, substantial discussions on the relevant interests and stakes concerning substantially increasing the share of H_2 have been commenced. These discussions highlight the possible conflicts that have to be considered and have to be continued. Based on these discussions, clear decisions in a European context have to be made, e.g. whether and when a blended gas system will be established or which pathway for blending will be chosen. While the details of a blended system cannot be determined at once, first essential decisions – e.g., which pathways are forsaken or the timetable for further decisions – are crucial as a base for further developments. Besides of these discussions and political decisions, the costs for technical adjustments to allow increased shares of H_2 have to be addressed to take advantage of renovation cycles. The permitting procedure for increasing the share of H_2 in the transmission system should be simplified like in § 43f (2) EnWG; to inform the planning phase of the TSOs, such a mechanism should be established rather soon. Moreover, the remaining uncertainties in regard to the gas definition of the EnWG have to be removed.
- At an **early stage** and based on the first essential decisions on the blending pathway, the details of the coordination to increase H_2 in the gas system and of the new regulatory framework for the blended system have to be established. Since the framework for the new blended system has to be in place before the share of H_2 is increased, the coordination of the operational change to increased shares of H_2, the design of the new legal framework and the necessary technical adjustments have to be pursued simultaneously.
- In the **long run**, details of the legal framework for the blended system can be adjusted to further developments, actual experience and new policy choices, e.g. to aim at further increases of the share of H_2. However, the main part of the challenging legislative work to enable increased shares of H_2 in the gas system has to be completed much more promptly.

4.3 Base Option 3: Dedicated H_2 Transmission Pipelines (Backbone)

4.3.1 Legal Background

The legal framework for dedicated H_2 transmissions pipelines is shaped by **extreme legal uncertainty** due to unclear scopes of application and fuzzy demarcations. The European as well as the German legislator did not have dedicated H_2 pipelines in mind. This legal uncertainty is a significant hurdle to investments in a dedicated H_2 system in its own right [BEN20a; ROS20], even though the possible legal differences are mostly limited. Moreover, the legal uncertainty shapes the further examination of the legal framework for a dedicated H_2 backbone, which has to consider different legal interpretations and to put a stronger emphasis on the potential for future developments.

At **EU level**, the natural gas regime and the electricity regime have to be considered in respect of dedicated H_2 networks. Pursuant to its article 1 (2), the scope of the Natural Gas Directive (and concurrently of the Natural Gas Transmission Network Regulation) extends to other gases if these can technically and safely be injected into, and transported through the natural gas system. While there is a broad understanding that H_2 is a gas that is covered by the Natural Gas Directive, there is an ongoing argument whether the EU natural gas regime also extends to dedicated H_2 networks. It has been argued that the extension of scope to other gases also encompasses the respective networks of these gases [FLE18a; RON20]. Yet, the wording, the specific aim of the legislator at the natural gas transport market situation and the details of the provisions (e.g., article 36 Natural Gas Directive) strongly favour an interpretation, which includes H_2 only in the context of actual natural gas systems and not in the context of a dedicated H_2 system [BEN20a; FLE20]. Nevertheless, H_2 pipelines and other dedicated components can be covered by the EU natural gas regime if they serve the natural gas transport market (for blending the H_2). This situation raises the issue of the demarcation between the dedicated H_2 systems that are not covered by the EU natural gas regime and H_2 system components that are covered by the regime. The legal context gives little hints on this issue and creates legal uncertainty [BEN20a]. The new Directive (EU) 2019/944 (Electricity Directive) also covers H_2 in the context of energy storage (see article 2 no. 59) [BEN20a; FLE18b]. Similarly to the situation for natural gas, the Electricity Directive certainly does not encompass a dedicated H_2 system but can cover individual H_2 components, which creates legal uncertainty in regard to the demarcation [BEN20a; FLE20].

At the **national level**, it is highly disputed whether and how far dedicated H_2 transmission pipelines are covered by the energy gas pipeline regime of the EnWG and the accompanying ordinances. The German legislator of the modern EnWG had clearly natural gas in mind. However, in contrast to the EU legislator in respect of the natural gas regime, the German EnWG has a much broader history and purpose and cannot easily be dismissed as a sector specific regulation for the natural gas transport market. In principal, three different approaches for interpretation – each with its own merits and drawbacks – can be identified: One approach does not apply the EnWG to dedicated H_2 transmission pipelines [BUN20b]. Closest to the literal reading of the EnWG, this approach applies the general pipeline – §§ 65–69 UVPG and its RohrFLtgV – and competition law – especially § 19 (2) no. 4 GWB – to dedicated H_2 transmission pipelines. Another approach wants to apply the complete natural gas regime (EnWG and all accompanying ordinances) to dedicated H_2 pipelines for energy purposes [KAL19; SIE20]. A third approach differs between natural gas specific provisions (especially in the context of market regulation), which are not applicable to dedicated H_2 pipelines, and general energy gas provisions, which are applicable to H_2 pipelines, in the EnWG [BEN20a]. The first two approaches provide a clear regulatory regime for dedicated H_2 pipelines but create clearly unwanted consequences (e.g., infringement of the Natural Gas Directive, non-sense differentiation between dedicated green hydrogen distribution systems and other dedicated H_2 systems for the first approach; integration of dedicated H_2 systems into the natural gas accounting cycle, bio-methane injection into dedicated H_2 systems for the second approach). The differentiating third approach, which also has the legislative history and the systematic context on its side, creates coherent results, but it also adds another layer of legal uncertainty at the level of individual provisions and demands challenging analyses.

Additionally, the unclear **gas definition** in regard to blue hydrogen (see section 4.2.1) deepens the legal uncertainty for dedicated H_2 systems.

The legal framework for dedicated H_2 transmission pipelines is shaped by legal uncertainty. At EU level, the demarcations between dedicated H_2 systems and (regulated) natural gas systems on the one hand and between dedicated H_2 systems and energy storage with power-to gas on the other hand are unclear. At the national level, the application of the EnWG to dedicated H_2 systems and the situation of blue hydrogen are unclear.

4.3.2 Construction and Repurposing

4.3.2.1 Legal Requirements for Construction and Repurposing

Regardless of the applicable pipeline regime, H_2 transmission pipelines have to comply with the **general provisions** of environmental law, construction law and regional planning that are relevant for all larger construction projects. Since H_2 is relatively similar to natural gas in its behaviour (gaseous, explosive, lighter than air, not water-pollutant), the specific requirements for dedicated H_2 pipelines are accordingly similar.

Pursuant to the **energy pipeline regime**, §§ 43 and 49 EnWG have to be considered. § 49 (1) EnWG demands that the pipelines are safe according to the state of the art. § 49 (2) EnWG refers to the technical rules of the DVGW; however, since there are no technical rules of the DVGW on

H_2 pipelines (yet), this reference is moot. The GasHDrLtgV gives further details on the safety requirements for transmission pipelines. For transmission pipelines with a diameter of more than 300 mm (see § 43 (1) sentence 1 no. 5 EnWG), the decision on a construction permit has to be based on a weighing of private and public interests pursuant to § 43 (3) EnWG; for this weighing, the goal of a reliable and economic supply with energy has to be considered appropriately. From a differentiating point of view, these provisions can be assigned to the general energy gas regime and are applicable to dedicated H_2 pipelines since they have no specific connection to natural gas [BEN20a].

Pursuant to the **general pipeline regime**, § 66 (1) UVPG in connection with no. 19.5 of its Annex I has to be considered. This stipulation requires that a pipeline with a diameter of more than 300 mm does not endanger public or private goods according to the state of the art. The construction permit has to be based on a weighing of relevant interests. Furthermore, § 66 (1) UVPG highlights the consideration of occupational safety and other legal requirements (which are applicable anyway). The RohrFLtgV reiterates the safety requirements and gives further details. The rules of the RohrFLtGV are applicable to all transmission pipelines (even with a diameter of less than 300 mm).

In **comparison**, the legal requirements of the different regimes do not differ much. There are some differences in respect to details, but their effect is limited: The reference to technical rules of the DVGW in the energy gas regime is moot anyway; and while energy projects are generally privileged by the EnWG whereas there is no corresponding privilege for general pipeline projects, the role of H_2 as an energy carrier can also be considered in the weighing of interests pursuant to § 66 UVPG. In essence, for all relevant pipeline regimes, the pipelines have to comply with general legal requirements, they have to be constructed safely according to the state of the art and the construction permit of larger pipelines has to be based on the weighing of relevant interests, especially the environmental impact.

Further requirements have to be met if an existing natural gas transmission pipeline is **repurposed**. In this case, the loss of the natural gas transmission pipeline has to be observed as well. The TSOs are responsible to maintain a network that is able to reliably meet the transport needs of the gas transport customers, see § 15 (3) EnWG. They may not cancel the use of a natural gas transmission pipeline if it endangered the reliable supply of natural gas. Therefore, the repurposing of a pipeline is only admissible if the requirements for removing the natural gas pipeline are also met. Especially pipelines that are foreseen by the NDP are considered necessary for a reliable supply of natural gas and therefore cannot be removed without respective evidence or adjustments of the NDP [BUN20b].

Dedicated H_2 transmission pipelines have to be constructed safe according to the state of the art and comply with further legal requirements for large constructions, especially environmental law. Additionally, large pipelines have to be based on a weighing of interests. These requirements correspond for all possible pipeline regimes; thus, the legal uncertainty does not have a substantial effect in this context. For repurposing, it is additionally required that the removal of the natural gas transmission pipeline does not impair the reliable supply of natural gas.

4.3.2.2 Permitting Procedure

For all transmission pipelines, the respective ordinances provide a **preliminary procedure** before construction. Pursuant to the natural gas regime (and the general energy gas regime), § 5 GasHDrLtgV demands to report the construction eight weeks before its start. Pursuant to the general pipeline regime, § 4a RohrFLtgV also demands a concurrent reporting eight weeks before the start of construction.

For the **construction of smaller transmission pipelines** (with a diameter of less than 300 mm), there is no specific permitting procedure for pipelines. Thus, the different potential pipeline regimes have no consequences insofar. Rather, general construction procedures have to be complied with.

Pursuant to § 43 (1) sentence 1 no. 5 **EnWG** – also as an expression of the general energy gas regime –, the **construction of large pipelines** (with a diameter of more than 300 mm) is permitted by a planning decision procedure according to §§ 72–78 VwVfG and the energy specific modifications of §§ 43a–43k EnWG. The planning decision procedure concentrates different permitting procedures and in general demands a public participation. For the most part, the specific modifications of the EnWG are options to simplify the permitting procedure. Pursuant to § 15 ROG in connection with § 1 no. 14 RoV, a preliminary regional planning procedure, which examines the compatibility of the project with regional planning, can be ordered if the construction of the respective energy gas transmission pipeline is regionally significant. Furthermore, an environmental impact assessment can be integrated in the procedure if the respective requirements of the UVPG are met. For pipelines that do not demand for an environmental impact assessment, the procedure can be simplified pursuant to § 74 (6) VwVfG, i.e. the public participation can be omitted, if the relevant private and public interests are considered and the competent authority decides so.

Under the **general pipeline regime**, pursuant to § 65 (1) UVPG, the **construction of large pipelines** is also permitted by a planning decision procedure according to §§ 72–78 VwVfG. The only modification of the planning decision procedure in the general pipeline regime regards the simplification of the procedure: Pursuant to § 65 (2) UVPG, a public participation will not be performed if an environmental impact assessment is not due, regardless of other interests and the discretion of the competent authority. Whether an environmental impact assessment is due, is determined by the UVPG. Moreover, the RoV does not foresee a regional planning procedure for general pipelines.

In **comparison**, the permitting procedures for the construction of large pipelines in the different pipeline regimes are quite similar. The basic procedure is the planning decision procedure with public participation according to §§ 72–76 VwVfG. The environmental impact assessment follows the same rules, criteria and thresholds under all possible pipeline regimes; insofar, the legal uncertainties have no consequences. There are significant differences between the possibly applicable regimes in regard to the specific options of the EnWG to accelerate and facilitate the procedure; yet, in this respect, the pipeline planners are free to decide whether they want to waive these options to avoid legal uncertainty. The regional planning procedure is only due under an energy pipeline regime. However, the consequences of this legal uncertainty are limited to the actual process: Since this procedure only facilitates the coordination of different authorities, third parties cannot challenge the final planning decision in regard to the omission or execution of a regional planning procedure. A more relevant difference concerns the possible simplifications in regard to the public participation: For the construction of a pipeline for which no environmental impact assessment is necessary, the competent authority has to omit the public participation pursuant to the general pipeline regime while it has to consider further requirements and make a discretionary decision on the participation pursuant to the energy gas pipeline regime. If the competent authority conducts a public participation, the pipeline planners lose the respective acceleration of the procedure (possibly cumulating with the waiving of acceleration options to reduce legal uncertainty) but there are no further risks due to legal uncertainty involved. If the competent authority omits the public participation solely based on the application of the general pipeline regime of the UVPG, the planning decision might be challenged by third parties at court due to procedural errors under the application of the EnWG.

The **competent authority** for the planning decision procedure is designated by the Länder. Whether the competent authority deviates depending on the applicable regime, is thus determined by the respective provisions of the individual Länder. For some Länder, the general district authorities are competent for all planning decision procedures for pipelines (although the responsibilities within the respective authorities due to internal organisation may still differ), e.g. in North Rhine-Westphalia pursuant to § 1 (2) Verordnung zur Regelung von Zuständigkeiten auf dem Gebiet des Energiewirtschaftsrechts under the energy gas pipeline regime and pursuant to § 4 Competence Ordinance for Environmental Protection (ZustVU NRW) in connection with its Annex II no. 7.7.2 under the general pipeline regime. Länder with other administrative structures and specialized authorities can also designate the competence for planning decision procedures for pipelines under different regimes to the same authority, e.g. in Lower Saxony, the LBEG is the competent authority for planning decision procedures pursuant to no. 11.1.2 Annex ZustVO-Umwelt-Arbeitsschutz under the energy gas pipeline regime and pursuant to no. 10.1.1 Annex ZustVO-Umwelt-Arbeitsschutz under the general pipeline regime. Yet, the competent authority according to the different regimes may differ, e.g. in Bavaria, where the regional general authorities are competent for energy gas pipelines pursuant to § 42 (1) Competence Ordinance (ZustV) while the counties or the general authority of Upper Bavaria are competent for other gas pipelines pursuant to § 51 (4) ZustV; in these cases, the legal uncertainty in respect of the applicable regime produces confusion right from the start of the procedure.

The **repurposing** of natural gas transmission pipelines to dedicated H_2 pipelines, as a change of the pipeline, also triggers the respective procedures. For all transmission pipelines, a repurposing has to be reported to the competent authority in a preliminary procedure pursuant to §§ 8, 5 GasHDrLtgV or § 4a RohrFLtgV respectively. For large pipelines with a diameter of more than 300 mm, a planning decision procedure is due pursuant to § 43 (1) sentence 1 no. 5 EnWG or § 65 (1) UVPG respectively. An environmental impact assessment is due – parallel to the increase of the share of H_2 (see above section 4.2.2) – if an environmental impact assessment was performed for the original natural gas transmission pipeline; no impact assessment is necessary for old or environmentally irrelevant pipelines. Like for the construction of new H_2 pipelines, the provisions for the simplification of the procedure differ depending on the pipeline regime: Under the energy pipeline regime – and parallel to the increase of the share of H_2 –, a simplification pursuant to § 74 (6) VwVfG (no public participation) or pursuant to § 43f EnWG (only reporting) can be chosen by the competent authority if there is no environmental impact assessment and the relevant interests are sufficiently considered otherwise; under the general pipeline regime, there is no public participation if there is no environmental impact assessment pursuant to § 65 (2) UVPG while – pursuant to pursuant to § 65 (2) sentence 2 UVPG in connection with § 74 (7) sentence 2 VwVfG – no planning procedure is due if there is no environmental impact assessment and the relevant interests are sufficiently considered otherwise. These differences create legal uncertainty in the case that the competent authority omits a public participation only because it applies the general pipeline regime although the requirements of § 74 (6) VwVfG are met – just like for the construction of new pipelines. In regard to further simplifications (§ 43f EnWG or § 65 (2) sentence 2 UVPG), the pipeline planner can avoid most legal uncertainty if it reports the repurposing nevertheless, and the competent authority can avoid most of the remaining legal uncertainty if it substantiates its reasons for not demanding a planning decision procedure. Legal uncertainty and the possibility of a legal challenge by a third party only poses a problem if the competent authority would have demanded a planning decision procedure under an energy pipeline regime but applies the general pipeline regime and performs no procedure. The RoV does not foresee a regional planning procedure for repurposing since it solely addresses constructions.

Thus, just like for the increase of the share of H_2 in the natural gas transmission system, the complex and cumbersome basic planning decision procedure is due for repurposing large natural gas pipelines unless there is no environmental impact assessment. Therefore, as a **remedy for this procedural burden**, the application of § 43f (2) sentence 1 no. 1 EnWG is discussed in this context. However, the provision is aimed at power lines and not applicable to the change of gas quality (see section 4.2.2). Yet, also for repurposing, the introduction of a similar mechanism by the legislator in which a preliminary procedure examines the safety of the gas transition, replaces the environmental impact assessment and allows the simplification of the procedure (e.g., by extending § 43f (2) EnWG) can be considered. Whereas there is a less pressing need for simplification in this context since there will be no concurrent operational change for the whole of the existing natural gas transmission system, the basic mismatch between the complex procedure and the limited risk of environmental impacts due to the repurposing is comparable. The individual impact of the repurposing of a single pipeline on the (natural) gas supply might be more significant than the operational change of a single pipeline within a universal change, and this significance might ask for a respective examination by the competent authority. However, these aspects can be taken into account by the new mechanism: E.g., in the context of § 43f EnWG, the competent authority can still chose to conduct a basic planning decision procedure if it deems a complex procedure with public participation more suitable for the weighing of different interests.

The core of the permitting procedure is not influenced by the lack of clarity in regard to the applicable regime. For the construction of large H_2 *transmission pipelines a planning decision procedure is required. Whether an environmental impact assessment is due, depends on the provisions of the UVPG with uniform criteria and thresholds. For repurposing large natural gas transmission pipelines to dedicated* H_2 *transmission pipelines, a planning decision procedure is due. If an environmental impact assessment was conducted for the construction of the original natural gas pipeline, this procedure entails an environmental impact assessment. Simplifications for the planning decision procedures for construction and repurposing are possible if an environmental impact assessment is not due. Under all regimes and for all cases, a preliminary reporting procedure is due. The differences of the relevant pipeline regimes refer to the energy specific facilitations of the EnWG, which can be ignored to avoid legal uncertainty, and individual aspects, which are contextually (e.g., regional planning procedure for regionally significant pipelines, public participation without environmental impact assessment) or locally (e.g., competent authorities in Bavaria) limited but can still create substantial legal uncertainty for the specific pipeline project. Additionally and similarly to a substantial increase of the share of* H_2 *in the natural gas transmission system, the procedure for repurposing could be simplified by legislative action.*

4.3.2.3 Expropriations and existing legal relationships

Under article 14 (3) German Constitution (GG), expropriations for compensation – even in favour of private agents like TSOs – are possible if they serve a public good. Expropriations demand a clear legal basis and may not go beyond the intervention that is necessary to pursue the public good. Therefore, for gas pipelines, real property is usually not expropriated as a whole. Rather, a restricted personal easement pursuant to §§ 1090–1092 Civil Code (BGB) is established, which allows using the property for the construction and the operation of the pipeline. Under the natural gas pipeline regime, **expropriations for the construction of new pipelines** are possible pursuant to § 45 EnWG if they are necessary for energy supply and the effective supply of energy outweighs the interests of the owner. A respective planning decision predetermines the necessity and priority of the pipeline project. The §§ 44a, 44b EnWG flank the expropriation regime of the EnWG. Since the expropriation regime of the EnWG has no specific relation to natural gas, it is also applied to the construction of dedicated H_2 pipelines under the differentiated approach. Under the general pipeline regime, there is no federal provision for expropriations in regard to gas pipelines and

Länder law is applicable; and on Länder level, clear legal bases for expropriations in respect of H_2 pipelines cannot be observed on a broad scale. Thus, the differences between the energy gas regimes and the general pipeline regime in regard to expropriations are very significant. The resulting legal uncertainty is relevant although the transfer of property rights is usually negotiated without sovereign expropriation, since the potential expropriation is often the starting point of the negotiations.

If natural gas pipelines are repurposed for the transport of H_2, it has to be examined how the **repurposing affects existing expropriations** in respect of the repurposed pipeline. In principal, once the purpose of the expropriation ends, the expropriated goods and rights have to be returned to the original owner. Thus, the restricted personal easements that allow the operation of the pipeline has to be erased, once the pipeline is not used anymore. Under the EnWG, the repurposed pipelines still serve the public good of energy gas supply. Therefore, the expropriations can still be based on the same basis and the original expropriations remain valid, regardless of the actual quality of the transported energy gas. Under the general pipeline regime, the situation is more complex: Although the actual purpose of the pipeline remains stable (energy gas supply), it is questionable whether the expropriations remain valid if the new use is not covered by the original legal basis for expropriation, especially if there is no legal basis for expropriation in regard to the new use. A new sovereign decision on the expropriation could create legal certainty but demands a respective legal basis. A legislative solution to create legal certainty would have to include the federal level and clarify that the supply with H_2 is considered energy supply in the context of § 45 EnWG and in regard of the purpose of the expropriation.

Another issue in this context is how the **repurposing affects negotiated contracts** in respect of the use of the pipelines. Transmission pipelines are imbedded in a number of negotiated agreements, e.g. to allow the construction and operation of pipelines in foreign property, to allow access to the pipelines for surveillance and maintenance or to specify the relation with crossing infrastructure. Many of these agreements anticipate possible expropriations. If an agreement is not applicable to dedicated H_2 pipelines, a surrogate solution has to be found. The question whether the respective contracts are also applicable to dedicated H_2 pipelines has to be examined on a case-to-case basis. For restricted personal easements, § 1091 BGB stipulates that the right should be interpreted in the light of the needs of the entitled person unless indicated otherwise; in an unclear contractual situation, this provision favours the extension of the restricted personal easement to the transport of H_2 [FNB20]. Nevertheless, the case-to-case examination creates legal uncertainty and demands substantial additional effort for the respective parties. This legal uncertainty is deepened by the legal uncertainty in regard to the effects of repurposing on expropriations since many contracts have to be interpreted in the light of the expropriation regime, which they anticipate.

The most direct way to address the possible effects of repurposing on negotiated contracts and the connected legal uncertainty is to **renegotiate the agreements** to expressively include H_2. This measure can also cover adjustments in regard to details or reimbursements if the repurposing has any relevant effect on the interaction between the TSO and the third party. Pursuant to § 313 BGB, the parties of a contract even have a right to appropriate adjustments if the original contract does not fit the changed situation anymore and it can be assumed that the contract would have included the adjustments if the changes had been foreseen. This provision can prevent blockades by unwilling third parties and extortionate negotiations. For agreements that anticipate possible expropriations, in most cases, the right to adjustments will depend on the scope of the expropriation and therefore refers to the respective legal uncertainty. For other agreements, in most cases, the TSO will have a right to have the contract adjusted to include H_2 unless the transport of H_2 has significantly different effects on the other party or the agreement has a specific link to natural gas. To sum it up, negotiated adjustments of contracts can create legal clarity but are still connected to substantial effort. The right to adjustments pursuant to § 313 BGB can hedge the position of the TSO and avoid purely interpretational conflicts but refers to further case-to-case examinations and legal uncertainty.

To tackle the effects of repurposing on negotiated agreements, **legislative actions** can be considered. It has been proposed to introduce a rule of interpretation that extends agreements in regard to natural gas pipelines to dedicated H_2 pipelines unless it can be proven that the agreement was not meant to include H_2 [FNB20; ROS20]. In addition to § 1091 BGB, this adjustment could clarify some situations and strengthen the position of the TSO without the need to renegotiate. Yet, this solution still requires a case-by-case examination of the contracts and cannot avoid the accompanying efforts and legal uncertainty. Besides, it has no effect on agreements that clearly address natural gas. To introduce such a rule of interpretation, rather shifts the issue than resolves it. Moreover, any retrospective rules of interpretation – even if it just clarifies an unclear situation – or straightforward stipulations on the content of an agreement would be legally and politically problematic as a sovereign intervention in existing legal relationships and rights. To improve the legal situation in regard to contracts, rather procedural mechanisms can be considered that create legal certainty and filter unproblematic cases without directly touching the substantial legal relationships: E.g., a stipulation could demand that the contracting party has to voice any reservations against the coverage of dedicated H_2 pipelines within a time period – possibly even connected to a duty to justify the reservations – and provide that otherwise the agreement is legally considered to also cover H_2 pipelines.

The expropriation regimes of the different potential pipeline regimes differ greatly, which creates substantial legal uncertainty. Private negotiations can remove this uncertainty but are easily impaired, especially since the legal uncertainty in regard to expropriations can also affect the negotiations. Especially in the case of repurposing natural gas pipelines, the legal uncertainty is an issue since the consequences of the repurposing on existing expropriations and agreements cannot be determined safely. For repurposing, contracts in respect of the operation of the pipeline demand a case-by-case examination, which deepens the legal uncertainty and creates additional costs. This situation cannot be avoided but might be mitigated by appropriate legislative action.

4.3.2.4 Costs of Construction and Repurposing

The creation (or spatial extension) of a dedicated H_2 transmission network by constructing new H_2 pipelines and repurposing existing natural gas pipelines is connected to high investment costs and the special circumstances of an emerging market (e.g., a small but growing number of customers, a lack of proven business models, low predictability). In comparison with the classical context of tariffs regulation as an operational issue, which aims at the maintenance and the development of an established network, this creation generates **specific challenges** despite many overlaps. At the core of these challenges, the attribution of costs has to be considered: Have the TSOs to bear the costs in the end (which would hinder investments) or can they pass on the costs to the customers of their dedicated H_2 system (which would create substantial risks for the first customers), to their gas transport customers in general, to all gas transport customers (in Germany) or to the state. Closely connected to this issue, it has to be considered how the repurposing of natural gas pipelines is handled from the perspective of the tariffs regulation for the natural gas system.

Under the current law, the attribution of costs depends on the applicable pipeline regime. For the repurposing of natural gas pipelines, according to the natural gas transmission pipeline regime, the costs will remain with the TSOs (see section 4.2.2). Particularly, the costs for adjusting the pipelines for the transport of H_2 cannot be considered investments costs pursuant to § 23 Incentive Regulation Ordinance (ARegV) [KAL19], which may be counted for the revenue ceiling, since the repurposing has no positive effect on the supply with gas (i.e. the natural gas pipeline that is to be repurposed already can sufficiently supply customers). According to the general pipeline regime, which has no specific tariffs regulation, the TSO can pass on the costs of repurposing a natural gas pipelines to the customers of the newly dedicated H_2 pipeline. The differentiated view on the applicable law does not apply the tariffs regulation regime for natural gas to dedicated H_2 transmission pipelines (see below section 4.3.3) and therefore follows the general pipeline regime in regard to the attribution of costs. In any way, the costs of adjusting natural gas transmission pipelines for the dedicated transport of H_2 cannot be passed on to a wider class of gas transport customers. In respect of the construction of new dedicated H_2 transmission pipelines, a similar situation can be observed. Without tariffs regulation, the general pipeline regime and the differentiated approach allow the TSOs to pass on the costs of construction to their H_2 transport customers. Whereas, under the natural gas regime, the TSO cannot pass on the costs of construction to others. Possible exceptions are dedicated H_2 pipelines which also address general congestions. In this case, the costs might be passed on to the customers as investments pursuant to § 23 ARegV; yet, it cannot be determined with certainty whether this passing-on only refers to the H_2 transport customers or all gas transport customers under a common revenue ceiling. Overall, under the current law, a high degree of legal uncertainty can be observed in respect of the attribution of costs, and – possibly except for special circumstances – costs cannot be attributed to stakeholders beyond the respective TSOs and their H_2 transport customers.

While **legislative action** is clearly needed in this regard, there is an array of possible legal mechanisms to finance the creation of a dedicated H_2 transmission networks [BUN20b]. At least, a clarification is needed that the TSOs can pass on the costs of the construction of new H_2 pipelines or repurposing natural gas pipeline to their H_2 transport customers. It can also be considered to pass on the costs to all customers of the respective TSO, e.g. by establishing a common revenue ceiling for H_2 and natural gas transport parallel to the situation for L-gas and H-gas [BUN20b]. However, if natural gas transport customers pay for dedicated H_2 pipelines, a TSO could use its position as a natural monopolist for natural gas transport to get an advantage on the new H_2 transport market. Such a cross-subsidization conflicts with the overall system of the market regulation for gas systems and possibly even infringes EU law [BEN20c]. In comparison to the situation for the L-gas and H-gas systems, which are spatially separated and established networks, H_2 transport is an emerging and expanding market and the dedicated H_2 pipelines can be concurrent to the natural gas system [BUN20b]. A Cross-subsidization can be avoided and the base for financing broadened – which reduces the costs for the individual stakeholder – by passing on the costs for creating a dedicated H_2 transmission network to the gas transmission system as a whole, acknowledging the responsibility of the whole gas sector for its progressing decarbonisation [SAD18] (see also section 4.2.2). For this purpose, § 19a EnWG for the transition of L- to H-gas can be used as a model [KAL19]; this provision also addresses a special burden on a distinct class of customers. A further option is to introduce subsidies – which would have to comply with EU subsidies law [SIE20] – or funding by the EU [EUR20] to cover at least a portion of the costs.

Additionally, in respect of the repurposing of natural gas pipelines, the perspective of the natural gas tariffs regulation has to be considered. The repurposed pipelines were **regulated assets** that were maintained and partly even constructed under the tariffs regulation regime. To exploit these assets outside of the regulated system has to be taken into account for the calculation of the revenue ceiling but clear provisions on this topic are missing [BUN20b]. Under a common revenue ceiling, this point is no problem at all; but especially in this context, the issue of cross-subsidization is manifest. Anyways, further legal action is needed to address and clarify this aspect.

In regard to the costs for the creation of a dedicated H_2 transmission network, the current legal framework is insufficient: It has a high degree of legal uncertainty and essentially does not allow attributing the costs to any other stakeholders but the customers of H_2 transport and the TSOs, which hinders the development of an H_2 market. Further legislative action is needed. The different legislative options are connected to further legal issues. At least, a clear legal basis to pass on the costs to the H_2 transport customers should be established. From a legal point of view, the simplest, most effective and coherent option is to pass on the costs to all gas transport customers like in § 19a EnWG. Additionally, it has to be considered from the perspective of the tariffs regulation of the natural gas system how the repurposing of a natural gas pipeline can be handled in regard to the exploitation of a regulated asset in a new market.

4.3.3 Operation

For the operation of transmission systems, the natural gas regime sports an extensive regulatory regime. Therefore, the analysis of this potential regime for dedicated H_2 transmission pipelines is in the focus of this section and will be supplemented and contrasted in regard to the other potential regimes.

An important aspect of natural gas market regulation is **unbundling**: Pursuant to § 6 EnWG, which implements the Natural Gas Directive, an effective separation of system operation and other market activities in the field of gas supply, especially supply, storage and trade, is demanded to ensure transparency and prevent discriminatory behaviour of the TSOs. Different models for unbundling are offered by §§ 8–10e EnWG. In regard to natural gas transmissions systems in Germany, the model of independent transmission operators is prevalent; it allows keeping the TSO in a vertically integrated group but prescribes manifold obligations to ensure effective operational independence of the TSO. In this context, TSOs for dedicated H_2 pipelines may not be engaged in other activities of an H_2 economy, especially not in H_2 production, storage and trade. This means that a TSO may not partake in activities on the supply or the demand side to foster the creation of an H_2 market. Accordingly, market participants in other parts of the supply chain, especially H_2 producers, may not be TSOs. However, unbundling does not demand a separation in regard to different transmission networks: Natural gas TSOs may be H_2 TSOs and vice versa.

As another central aspect of natural gas market regulation, TSOs have the duty to –without discrimination – connect third parties pursuant to § 17 (1) EnWG and to allow **third party access** pursuant to § 20 (1) EnWG to their transmission system. The duty to allow non-discriminatory third party access is extensively fleshed out by §§ 21–28a EnWG and the GasNZV. These stipulations also include the priority access of biogas pursuant to § 34 GasNZV. Similar to the blending of H_2 in the natural gas transmission system, the respective privilege for green hydrogen has the potential to repress blue hydrogen; but since a dedicated H_2 transmission network would be much more flexible than the blending option, this limitation will probably not be much of an issue. The question whether the biogas privilege is to be interpreted in a way that allows bio methane injection into dedicated H_2 transmission pipelines, which might jeopardize the system as a whole [KAL19] is a more problematic issue. Another H_2 related aspect of the third party access regime for natural gas are the accounting cycles according to §§ 22–26 GasNZV, which allow for balanced gas supply under the legal design of the EnWG for access and gas transport. The GasNZV only provides accounting cycles for biogas and natural gas and it is unclear how H_2 fits into this system [KAL19].

For natural gas, **tariffs regulation**, which is found in the EnWG, the Gas Network Tariffs Ordinance (GasNEV) and especially the ARegV, is extremely tight. The main mechanism is the revenue ceiling based on a comparison of different TSOs in a simulated competition. The application of this tariffs regulation to dedicated H_2 pipelines faces two significant issues: First, since a dedicated H_2 transmission network is not foreseen in the relevant stipulations, it is not clear whether the operation of an H_2 network and the operation of a natural gas network share a common revenue ceiling like in the case of L- and H-gas networks. Secondly, for dedicated H_2 pipelines, a comparison between different TSOs is in principal possible, but the lack of established classes of comparable TSOs in the emerging H_2 market can create problems for the actual execution of the comparison [BUN20b].

The narrow limits for TSOs in the tight natural gas market regulation is eased by the possibility of **regulatory holidays** for new infrastructures pursuant to § 28a EnWG in connection with the Natural Gas Directive. The goal of the possible exemption from regulatory provisions is to enable large and risky investments that improve the overall gas supply. Theoretically, it can be discussed whether the reference to the Natural Gas Directive excludes the application of the regulatory holidays to dedicated H_2 transmission pipelines. From a practical point of view, the requirements for the regulatory holidays aim at specific investments in the natural gas system and have no or little relevance for an emerging H_2 system anyway. Thus, although the addressed situations are structurally comparable to the creation of an H_2 transmission network as a whole, regulatory holidays have no significant effect for dedicated H_2 transmission pipelines. This mismatch creates an inadequate disadvantage for dedicated H_2 pipelines in regard to large and risky investments [BEN20a].

Closely related to the natural gas market regulation regime is the **abuse control** regime according to §§ 30–35 EnWG, which provides the material and procedural framework to control abuses by the TSOs of their natural monopolies. Yet, the actual connection between market regulation and abuse control is limited to single references. Rather, the abuse control regime of the EnWG adjusts the abuse control regime of the general competition law to the situation of network-based transport of energy and its administrative framework.

As a specific aspect of the operation of energy networks, § 11 (1) EnWG stipulates the duty of the TSOs to ensure a secure, reliable and efficient supply of energy. This **system responsibility** of the TSOs is amended and fleshed out by further stipulations as well as flanked by state supervision. Under the natural gas regime, the TSOs are obliged to participate in a **strategic planning** process. Pursuant to § 15a EnWG, the TSOs have to develop the NDPs (see section 4.2.3), which are based on assumptions on demand, supply and transportation needs, have to be approved by the BNetzA and are the basis for the European strategic planning. They are the basis of the state supervision in regard to system responsibility, § 65 (2a) EnWG. In regard to dedicated H_2 pipelines, the development of H_2 demand, supply and transportations needs are – especially in comparison with natural gas – barely foreseeable and rather vague [BEN20a; BUN19; GRÖ20]. The presentation of dedicated H_2 pipeline networks in NDPs is therefore harder and it cannot be ruled out that the disadvantage in regard to representability will also hinder the planning and the actual realization of dedicated H_2 pipeline networks. Additionally, in the case of repurposing, the loss of natural gas transport capacities has to be considered in the NDPs in respect of natural gas [BUN20b]. An instrument of strategic planning of cross-border energy infrastructure are PCIs under the TEN-E Regulation. Although these are not applicable to H_2 pipelines under the current TEN-E Regulation, its revision could incorporate H_2 projects [EUR20].

The operation of natural gas pipelines – like their construction – has to be safe. **Safety requirements** are provided by § 49 (1) EnWG and the GasHDrLtgV (§§ 2, 4, 9, 10), which has a focus on major accidents and stipulates duties of TSOs in regard to the prevention and reporting of major accidents. For dedicated H_2 pipelines, the reference of § 49 (2) sentence 1 no. 2 EnWG to the technical rules of the DVGW is moot since there are no technical rules of the DVGW on H_2 pipelines yet.

The **administrative framework** in respect of the operation of natural gas pipelines is shaped by the general competence of the regulatory authorities (especially the BNetzA) in regard to specific aspects of the network operation and transport market, while the Länder are competent in regard to rather technical issues like safety. Additionally, §§ 75–93 EnWG establish a special legal action regime in respect of the regulatory authorities, which concentrates all legal actions against the regulatory authorities at the Higher Regional Courts.

The **differentiated approach** has to examine the plethora of provisions in regard to the operation of natural gas transmission pipelines and decide on their applicability to dedicated H_2 transmission pipelines on a case-to-case basis. In this regard, certain general lines can be observed. Most stipulations of the EnWG on the operation of transmission networks, especially in respect of safety and system responsibility, address general conflicts of the energy industry or the specific situation for the supply with energy gas and can rather be attributed to a general energy gas regime that also encompasses dedicated H_2 pipelines [BEN20a]. However, there are substantial exceptions: rules that are specifically aimed at the supply of natural gas and its market. These rules form a specific natural gas regime, which – according to the differentiated approach – is not applicable to dedicated H_2 transmission pipelines. This specific natural gas regime, which is not applicable to dedicated H_2 pipelines includes, e.g., the provisions on strategic planning and NDPs [BEN20a]. Especially, most parts of the natural gas market regulation (unbundling, third party access, tariffs regulation) are a specific reaction to the natural gas market and cannot be extended to dedicated H_2 pipelines [BEN20a]. Whereas, general principles that transfer general principles of competition law to the specific situation of gas networks, and their specification, especially the principle of non-discrimination and the abuse control regime, are parts of the market regulation, which are applicable to dedicated H_2 transmission pipelines [BEN20a]. Since the rules on unbundling are not applicable to dedicated H_2 transmission pipelines, TSOs for H_2 transport can in theory be active in every other part of the H_2 supply chain. In practice, unbundling will be considered anyway: First, unbundling will probably be introduced once the H_2 market matures and TSOs will try to avoid adjustment costs; secondly and more importantly, H_2 TSOs will probably be the TSOs for natural gas transport and these are not allowed to engage in the supply chain of H_2, which can also be injected into the natural gas system [BUN20b]. There is some uncertainty on the question whether unbundling forbids the operation of regulated natural gas transmission pipelines and not regulated H_2 transmission pipelines at the same time [FNB20; RON20], but there is no basis for such a prohibition since both activities only cover the transmission of gas [BUN20b].

The **general pipeline regime** has no specific rules for pipeline operation besides safety requirements. There are no provisions on the security of supply (system responsibility). And instead of a market regulation regime, the general competition law is applicable, which also provides a principle of non-discrimination [BUN20b]. Especially § 19 (2) no. 4 GWB, which prohibits discrimination of competitors by the operators of networks, has to be considered: Although the existing TSOs are not competitors to their (potential) transport costumers, the overarching vertically integrated groups are. The safety stipulations for the pipeline operation, especially §§ 3, 4, 7 RohrFLtgV, are – similar to the situation for the construction of pipelines – essentially parallel to the natural gas regime.

The **comparison** of the different pipeline regimes reveals that the legal uncertainty due to the unclear applicable regime is very significant in respect of the operation of the pipelines. The natural gas regime provides ample stipulations on the operation, including safety requirements, system responsibility and extensive market regulation. Some of these stipulations do not match the situation for the emerging H_2 market, which adds to the legal uncertainty since the legal consequences of this mismatch are not always clear. The general pipeline regime is rudimentary and does not consider the specific challenges of energy supply. The differentiated regime provides an essentially fitting regime, which considers the special challenges of energy supply as well as avoids provisions that are specifically aimed at natural gas and do not work for dedicated H_2 pipelines. However, it demands a case-to-case examination of the EnWG, which creates additional effort and legal uncertainty. Therefore, especially in respect of operation, the legal framework has to be developed. On a first step, the legal regime has to be clarified. This clarification should also consider the appropriateness of the legal framework for dedicated H_2 pipelines. For this purpose, the differentiated approach provides a workable starting point. Accordingly, the focus of the clarification should be put on the identification of stipulations of the EnWG and its ordinances that are specifically aimed at natural gas and which constitute a general energy gas regime, without putting much (or any) emphasis on a specific H_2 regime. Since one of the main sources of the legal uncertainty in respect of H_2 and the EnWG is the historically conditioned unification of natural gas and energy gas, this approach starts at the actual legal problem. It also upholds technology neutrality and is not based on elaborate details for an H_2 market, on which there are no experiences. Therefore, this approach of clarification is rather technical and less political, needs little effort and can be executed in short time. On a later second step, specific adjustments for dedicated H_2 transmission pipelines can be taken into account, creating a specific H_2 regime. E.g., NDPs are shaped for natural gas and the according stipulations do not consider the specific challenges in respect of the predictability of H_2 developments in an emerging market. Yet, NDPs as a mechanism for strategic planning facilitate and enhance the development of transmission networks and are especially important in respect of H_2 [BUN20b]. Therefore, the EU Commission considers NDPs for dedicated H_2 transmission networks on a European level [EUR20]. The stipulations on H_2 NDPs should consider the lack of predictability in a way that avoids disadvantages for dedicated H_2 pipeline networks. Also, since the need for regulating the natural monopolies of dedicated H_2 pipeline networks is manifest, a market regulation for H_2 pipelines should be developed at some point. However, the specific regulation for dedicated H_2 pipeline networks should react to the specific situation on the H_2 transport market and be based on specific experiences. Hence, there is no need to prerequisite an extensive market regulation besides general principles of non-discrimination [EUR20] and single regulatory stipulations before the start of the actual dedicated H_2 network. Rather, the regulation of the H_2 transport market should be seen as a learning process, which can start at the national level before it is consolidated at EU level. At this point in time, it seems inappropriate to transfer the existing natural gas regime to dedicated H_2 pipeline networks forcefully or to wait for further action at EU level.

In respect to the operation of dedicated H_2 transmission pipelines, the substantial differences between the potentially applicable regimes create significant legal uncertainty. The natural gas regime provides extensive rules on unbundling, third party access, tariffs, abuse control, safety requirements, system responsibility and manifold other details in respect of the operation of transmission pipelines. The general pipeline regime provides little more than safety requirements and a prohibition to discriminate. The differentiated approach provides a middle way with a case-to-case examination, which excludes most of the natural gas market regulation and is very close to the natural gas regime beyond that. This legal uncertainty demands legislative action. Furthermore, the legislative needs are informed by the detailed examination of the potential regimes: The natural gas regime often does not match the situation of dedicated H_2 pipelines and thus creates additional legal uncertainty, the general pipeline regime does not address the specific conflicts and challenges of energy supply and the differentiated approach is too demanding and legally uncertain. The needed development of the legal framework has to clarify the legal situation for dedicated H_2 pipelines without transferring inappropriate rules or ignoring important conflicts of the energy industry. As a first step, the demarcation of the natural gas regime against a general energy gas regime in the EnWG is recommended. This approach would clarify the legal situation, avoid the application of mismatching stipulations and consider specific conflicts in respect of energy supply.

4.3.4 Market

In regard to **CO_2 pricing**, the production of H_2 with a production capacity exceeding 25 tonnes per day and therefore the mitigation of CO_2 emissions by CCS for blue hydrogen are covered by the EU ETS, see no. 28 Annex I TEHG/Annex I EU ETS Directive. Since in a dedicated H_2 system CO_2 is emitted only at the production site, the benefits and costs of the mitigation measures can easily be attributed (see in contrast section 4.2.4 for blended H_2). Thus, in principal, there is a functioning framework for a market for CO_2 and CO_2 mitigation in regard to blue hydrogen in dedicated H_2 pipeline networks. Yet, the current EU ETS still sports some issues: Blue hydrogen in dedicated H_2 pipeline networks, which is addressed by the EU ETS at the production, has the same relative disadvantage in comparison with natural gas, which is addressed by the EU ETS at the usage, as blue hydrogen in blended systems (see section 4.2.4). Moreover, the threshold of 25 tonnes per day may produce false incentives in respect of scaling and mitigating CO_2 emissions at the production of H_2. The national pricing mechanism under the BEHG can mitigate the relative disadvantage and the false incentives, but may also create further issues in respect of the import of H_2.

At EU level, the RED II Directive foresees **guarantees of origin** only for renewable gases, including green hydrogen. For blue hydrogen, no guarantees of origin are foreseen, but there is an ongoing discussion on this issue (see section 4.2.4).

From a legal point of view, there are no major obstacles for an H_2 market that is based on a dedicated pipeline network since the costs and benefits of CO_2 mitigation measures can be easily attributed. However, improvements can be discussed in respect of guarantees of origin, false incentives in regard to the scale of production and relative disadvantages in comparison with natural gas under the EU ETS.

4.3.5 Assessment of Risks and Opportunities

The legal uncertainty, especially about the applicable regime, is the major legal obstacle to a dedicated H_2 transmission network. The impact of the legal uncertainty varies in different areas. In regard to safety, the different potentially applicable regimes are similar and the legal uncertainty has little effect. It is more significant in respect of competent authorities and expropriations. The effect is especially grave in regard to the operation of the pipelines since the natural gas regime provides an extensive market regulation and manifold stipulations on system responsibility. Anyways, the legal uncertainty will hinder concrete investments decision to implement a dedicated H_2 transmission network.

Independently of the applicable regime, a number of individual issues connected to dedicated H_2 transmission pipelines is not properly addressed by the current legal framework. The framework for strategic planning of transmission networks with NDPs does not consider the reduced predictability in regard to the emerging H_2 market. A full environmental impact assessment and planning decision procedure for repurposing existing large natural gas transmission pipelines is inappropriate in the light of its limited consequences. The costs of the creation of a dedicated H_2 transmission network are to be borne by the TSOs or arguably its H_2 customers although the once established network will be accessible to new customers and promotes the public interest of decarbonizing the economy. For repurposing, the handling of the existing legal relationship concerning the natural gas pipeline can be pointlessly burdensome.

In summary, under the current legal framework, the creation of a dedicated H_2 transmission network is not feasible. However, the necessary legislative amendments are rather simple, especially in comparison with the situation of the other infrastructure options. The legislative actions that are immediately necessary to enable the timely creation of an H_2 backbone are either rather technical measures, especially the clarification of the applicable regime, or very limited in their consequences, like the attribution of costs for the initial investments. These actions have little potential for conflicts and are a basis for later developments. The legislative actions that may be necessary later address points of limited potential for strong political conflicts (e.g., single regulatory aspects and NDPs), are given enough time for a thorough technical and political discussion (complete H_2 regulation) or are subordinate aspects to larger issues, which have to be addressed anyway (EU ETS). Neither from a technical nor from a political perspective, there are massive obstacles for a legal framework that allows the creation of a dedicated H_2 transmission network.

- **Immediate actions** have to be taken in respect of the construction of new H_2 pipelines or the repurposing of existing natural gas pipelines. Most issues in regard to the operation of dedicated H_2 pipelines can be addressed at a later stage as long as there is a reliable political commitment and a workable fall back regime. The most critical immediate action is the clarification of the applicable regime, especially in regard to expropriations, procedures and competences. It is strongly recommended to establish the EnWG as a general energy gas regime and demarcate the special natural gas regime (including adjustments to the gas definition). This course of action addresses the actual source of the legal uncertainty, creates a technologically neutral fall back regime and allows addressing specific H_2 issues in a separate discussion. At EU level, the demarcation of other regimes (natural gas, power storage) in relation to dedicated H_2 pipelines should be clarified. Additionally, the position of the existing dedicated H_2 pipeline networks for the chemical industry should be clarified in a way to avoid further confusions. Besides the clarification measures, the costs of investments for the creation of a dedicated H_2 transmission network have to be addressed. The respective new legal mechanism does not have to establish a final attribution of costs, but has to create a legally reliable financing framework as soon as possible; ideally, this mechanism involves all gas customers (e.g., based on the model of § 19a EnWG) or even public funding. The permitting procedure for mere repurposing of existing gas pipelines should be accelerated by replacing the environmental impact assessment by a simple procedure to investigate possible risks similar to § 43f (2) EnWG. In respect of repurposing, it is also recommended to create a legal mechanism to facilitate the handling of existing legal relationships concerning the natural gas pipelines. Moreover, while it is not necessary to immediately provide a market regulation for dedicated H_2 pipelines, the discussion on it – as it has been started by the BNetzA – should be continued and deepened. A secondary aspect, which should be considered soon, is a legal mechanism to curtail the tariffs for H_2 transport and protect future first investors on the customer side. This issue can be addressed in a regulatory context, although the mere transference of the ARegV to dedicated H_2 pipeline is questionable due to the lack of an established class for comparison. However, other legal contexts and financing mechanisms can be considered, too. Anyways, although a regulatory intervention is systematically not called for since potential customers of a future network are not facing a natural monopoly and have significant market power vis-a-vis future TSOs, a practical and workable solution can and should be found.
- Although there is no immediate need for an H_2 market regulation to enable the creation of a dedicated H_2 transmission network, the realities of a network-based economy, especially in the area of energy supply, will call for regulatory rules at an **early stage**. At the national level, an expanding and developing body of market regulation can react to experiences and developments in the emerging and growing H_2 market to address the challenges at hand. At EU level, guiding principles for H_2 market regulation should be formulated as an orientation for the national legislators and as guidelines for the market participants in

respect of future developments. Additionally, further adjustments to the legal framework to facilitate the orderly expansion of the H_2 backbone have to be considered. E.g., it is recommended, to create a strategic planning instrument that is equivalent to the NDPs for natural gas but takes the peculiarities of an emerging H_2 market into account. To connect these instruments with the ten years NDPs at EU level would support the efficient development of a European dedicated H_2 transmission network and the decarbonisation of Europe's industry. In addition to these measures, the possibility to acknowledge dedicated H_2 transmission pipelines as PCIs under a revised TEN-E Regulation would further an efficient development of a cross-border H_2 infrastructure. Also at an early stage, provisional rules for the start of the creation of dedicated H_2 networks have to be transferred to and transformed into stable regimes, e.g. a passing-on mechanism for the investments in dedicated H_2 pipelines or a final transition rules in regard to the existing H_2 networks.

- In the **long run**, a European H_2 market regulation will be inevitable. This market regulation should be based on the EU guiding principles and the regulatory experiences on the national level. Moreover, it should consider future developments of the energy market and the industry, which cannot be foreseen today.

4.4 Summary

For all three infrastructure options to integrate the German economy into H_2-CCS chains, the current legal framework is inappropriate and hinders their realization. However, the legal framework can be developed and adjusted by legislative action to allow the implementation of the three base options or at least similar infrastructure options.

The legal framework for the transport of CO_2, especially the KSpG, is not fit for the challenges of a multi-polar CO_2 pipeline network. Additionally, individual issues (especially the application of the London Protocol without provisional application of its 2009 amendment and the omission of ship transport in the EU ETS) unnecessarily hinder an effective cross-border CO_2 transportation network. While most of these barriers can be easily removed or leave enough time for a thorough legal and political discussion to properly address these challenges, the completion of an extensive and operational CO_2 pipeline network before 2035 is most unlikely due to the long planning and permitting procedures, even if ambitious actions are taken. Yet, shipping routes can replace pipelines; this point highlights the importance of the legal adjustments concerning ship transport of CO_2.

In regard to blending of H_2 in natural gas transmission pipelines, a plethora of provisions in the current legal framework for natural gas pipelines, which was not intended for more than marginal blending of any other gas, hinders the substantial increase of the H_2 share. To remove these barriers, very different approaches can be considered. However, any of these approaches intensely intervenes in the established system of gas supply. Most of the necessary adjustments are not pressed for time, but very challenging, susceptible to conflicts and therefore hard to implement. Anyways, the privileges for green gas will not allow much space for blue hydrogen in a blended system.

For the creation of a dedicated H_2 transmission network, the extreme lack of legal certainty is the major legal barrier. To tackle this systemic barrier, individual legal adjustments will not suffice. Rather, an extensive clarification is needed, which can also address the specific challenges of H_2 pipeline networks. The clarification and the specific challenges mostly address technical issues and respective legal adjustments can be realised rather smoothly. Thus, despite the stark need for legislative action, dedicated H_2 transmission networks are the most feasible infrastructure option from a legal point of view.

To produce valuable guideline for further recommended actions (see tables 4.1–2) out of the legal analysis, it is important to consider the timeline. Actions that have to be taken immediately and can be implemented in a short time have to be identified and highlighted. Recommendations in regard to actions at later stages might have to be adjusted or become obsolete due to further developments in an uncertain future. Accordingly, the recommendations for immediate actions focus on necessary political and scholarly discussions and – more importantly – on the creation of dedicated H_2 transmission networks, since time is of the essence in this area, the recommended actions are feasible and this infrastructure option is especially promising.

Table 4.1: Recommended actions in regard to the legal framework for CCS.

Action	**Area**	**Agents**
Immediate Actions		
Substantial discussion on political goals in regard to CCS * **	***CO_2 transport***	***Policy makers, society, industry***
Extension of EU ETS to CO_2 ship transport	***CO_2 transport***	***Legislator (EU)***
Provisional application of the 2009 amendment to the London Protocol	***CO_2 transport***	***Legislator (federal)***
Substantial discussion on legal technicalities in respect of multi-polar networks	*CO_2 transport*	*Policy makers, academia (legal), industry (emitters, pipeline operators, storage operators), legal practitioners*
Strong political signal on CO_2 networks	*CO_2 transport*	*Policy makers*
Early Stage		
Dissemination of experience and research	***CO_2 transport***	***Policy makers, academia, industry***
Political commitment to CCS goals	**CO_2 transport**	**Policy makers (federal)**
Establishment of principles for future multi-polar network operation	*CO_2 transport*	*Policy makers (EU, federal)*
Planning and Permitting of showcase CO_2 pipelines	CO_2 transport	Policy makers, industry (emitters, pipeline operators, storage operators)
Update and enhancement of procedure, esp. in respect of project managers, competences and uncertainties	*CO_2 transport*	*Legislator (federal, Länder)*
Adjustment of liability regime to pipeline situation	*CO_2 transport*	*Legislator (federal)*
Long Run		
Establishment of a pipeline operation regime for multi-polar networks	**CO_2 transport**	**Legislator (EU, federal)**
Expropriation regime for transit pipelines	*CO_2 transport*	*Legislator (federal)*

* Actions that are considered critical are printed bold.

** Actions that are considered low- or no-regret are printed in italics.

Table 4.2: Recommended actions in regard to the legal framework for H_2.

Action	Area	Agents
Immediate Actions		
Reliable political commitment to dedicated H_2 networks * **	***H_2 (dedicated)***	***Policy makers (EU, federal)***
Reform of gas definition in EnWG	**H_2**	***Legislator (federal)***
Clarification of the applicable regime, especially in regard to expropriations, procedures and competences (especially by re-establishing a general gas regime and demarcating the special natural gas regime)	***H_2 (dedicated)***	***Legislator (federal)***
Demarcation of other regulatory regimes (power storage, natural gas)	***H_2 (dedicated)***	***Legislator (EU, federal)***
(Initial) financing of H_2 adjustments	**H_2**	**Legislator (EU, federal)**
Simplified permitting procedure for changes in the quality of the transported gas (see § 43f (2) EnWG)	***H_2***	***Legislator (federal)***
First essential decisions on further pathway for blending	**H_2 (blending)**	**Policy makers (EU, federal)**
Substantial discussion on interests and stakes in respect of increasing the share of H_2	***H_2 (blending)***	***Policy makers, industry (customers, pipeline operators), society (customers)***
Demarcation of existing H_2 networks	*H_2 (blending)*	*Legislator (federal)*
Substantial discussion on the need to regulate H_2 networks	*H_2 (dedicated)*	*Policy makers, industry, academia, society*
Facilitate handling of existing legal relationship in the case of repurposing	H_2 (dedicated)	Legislator (federal)
Mechanism to limit tariffs for first H_2 customers	H_2 (dedicated)	Legislator (federal)
Early Stage		
Regulatory framework for dedicated H_2 networks	**H_2 (dedicated)**	**Legislator (federal)**
Financing of H_2 adjustments (see § 19a EnWG)	**H_2**	**Legislator (federal)**
Coordination of increase of H_2 share	**H_2 (blending)**	**Policy makers, legislator (EU, federal), industry (pipeline operators, customers)**
Coordination regime for gas quality	**H_2 (blending)**	**Legislator (EU, federal)**
Regulatory adjustments to blended systems	**H_2 (blending)**	**Legislator (EU, federal)**
Framework for strategic planning (NDPs) of dedicated H_2 networks	*H_2 (dedicated)*	*Legislator (EU, federal)*
Extension of TEN-E Regulation to H_2 projects	*H_2 (dedicated)*	*Legislator (EU)*
Establishment of principles for future EU-wide regulation	*H_2 (dedicated)*	*Policy makers (EU)*
Final transition rules for existing H_2 networks	*H_2 (dedicated)*	*Legislator (federal)*
Long Run		
EU H_2 market regulation	**H_2 (dedicated)**	**Legislator (EU)**
Adjustments of the regime for blended systems	H_2 (blending)	Legislator (EU, federal)

* Actions that are considered critical are printed bold.
** Actions that are considered low- or no-regret are printed in italics.

4.5 References

[ACE19] ACER; Council of European Energy Regulators: *The Bridge Beyond 2025. Conclusions Paper*. – URL: https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/SD_The%20Bridge%20beyond%202025/The%20Bridge%20Beyond%202025_Conclusion%20Paper.pdf. 2019.

[BAN19] Bankes, N.: *Provisional Application of an Amendment to the London Protocol to Facilitate Collaborative CCS Projects*. – URL: https://site.uit.no/nclos/2019/12/11/provisional-application-of-an-amendment-to-the-london-protocol-to-facilitate-collaborative-ccs-projects/. 2019.

[BEN19] Benrath, D.; Flamme, S.; Glanz, S. et al.: *German Case Study: Final Design and First Results*. – URL: https://www.sintef.no/globalassets/project/elegancy/deliverables/elegancy_d5.5.2_german-case-study_design_first-results.pdf. 2019.

[BEN20a] Benrath, D.: *Applicable law to hydrogen pipelines for energy purposes in Germany*. In: *Journal of Energy & Natural Resources Law* 38, pp. 65–89. – DOI: https://doi.org/10.1080/02646811.2019.1696519. 2020.

[BEN20b] Benrath, D.: *Paradigmenwechsel in der dauerhaften Speicherung von Kohloendioxid: vom besonderen Bergrecht zum besonderen Leitungsrecht*. In: Johann-Christian Pielow (ed.): Bergrecht im Wandel der Zeit: gestern - heute - morgen. Festgabe zum 200-jährigen Bestehen des OLG Hamm. Stuttgart: Boorberg, pp. 320–344. 2020.

[BEN20c] Benrath, D.: *Die Verbesserung der Wasserstofftauglichkeit des Erdgasfernleitungsnetzes. Der rechtliche Rahmen für Umbaumaßnahmen an der Erdgasfernleitungsinfrastruktur im Kontext erhöhter Wasserstoffanteile*. In: *Recht der Energiewirtschaft.* Forthcoming.

[BEN20d] Benrath, D.: *Blind Spots in the Harmonisation for an H2-CCS chain*. In: Bernard Vanheusden, Theodoros Iliopoulos und Anna Vanhellemont (eds.): Harmonisation in Environmental and Energy Law. Forthcoming.

[BOR20] Borning, M.: *Wasserstoff. Der Schlüssel für die Energiewende wartet auf die passende Regulierung*. In: *EnergieRecht*, pp. 108–116. 2020.

[BRA19] Brauner, A.; Benrath, D.: *A Legal Overview of The Construction, Operation and Regulation of Gas Transmission Grids in Germany*. In: *Oil, Gas & Energy Law Intelligence* 17 No. 5. – URL: https://www.ogel.org/article.asp?key=3854. 2019.

[BUC19] Buchmüller, C.; Wilms, S.; Kalis, M. et al.: *Der Rechtsrahmen für die Vermarktung von grünem Wasserstoff*. In: *Zeitschrift für Neues Energierecht*, pp. 194–204. 2019.

[BUN18] Bundesregierung: *Evaluierungsbericht der Bundesregierung über die Anwendung des Kohlendioxid-Speichergesetzes sowie die Erfahrungen zur CCS-Technologie. Unterrichtung durch die Bundesregierung*. Bundestags Drucksache 19/6891. – URL: http://dipbt.bundestag.de/doc/btd/19/068/1906891.pdf. 2018.

[BUN19] BUNDESNETZAGENTUR: *Bestätigung des Szenariorahmens für den Netzentwicklungsplan Gas 2020-2030*. 2019.

[BUN20a] BUNDESREGIERUNG: *Die Nationale Wasserstoffstrategie*. 2020.

[BUN20b] BUNDESNETZAGENTUR: *Regulierung von Wasserstoffnetzen. Eine Bestandsaufnahme der Bundesnetzagentur*. – URL: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/Wasserstoff/Wasserstoffpapier.pdf. 2020.

[EUR20] EUROPEAN COMMISSION: *A hydrogen strategy for a climate-neutral Europe*. COM(2020) 301 final. 2020.

[FLE18a] FLEMING, R.; FERSHEE, J.: *The 'Hydrogen Economy' in the United States and the European Union. Regulating Innovation to Combat Climate Change*. In: Donald Zillman, Martha Roggenkamp, Leroy Paddock et al. (eds.): Innovation in Energy Law and Technology. Dynamic Solutions for Energy Transitions. Oxford: Oxford University Press, pp. 137–153. 2018.

[FLE18b] FLEMING, R.: *Regulating Power-to-Gas in the Energy Union*. In: *Oil, Gas & Energy Law Intelligence* 16 No. 4. – URL: https://www.ogel.org/journal-advance-publication-article.asp?key=577. 2018.

[FLE20] FLEMING, R.; KREEFT, G.: *Power-to-Gas and Hydrogen for Energy Storage under EU Energy Law*. In: Martha Roggenkamp und Catherine Banet (eds.): European Energy Law Report. Cambridge: Intersentia, pp. 101–125. 2020.

[FNB20] FNB GAS; BDI; BDEW ET AL.: *Auf dem Weg zu einem wettbewerblichen Wasserstoffmarkt. Gemeinsamer Verbändevorschlag zur Anpassung des Rechtsrahmens für Wasserstoffnetze*. – URL: https://www.fnb-gas.de/media/fnb_gas_bdi_bdew_vik_dihk_auf_dem_weg_zu_einem_wettbewerblichen_wasserstoffmarkt_april_2020_final.pdf. 2020.

[GRÖ20] GRÖSCH, Y.; HORSTMANN, F.; MÜLLER, A. ET AL.: *Leitungsgebundener Transport von Wasserstoff. Eine Bestandsaufnahme*. In: *Recht der Energiewirtschaft*, pp. 174–177. 2020.

[HEN17] HENRIKSEN, D. E.; OMBUDSTVEDT, I.: *Cross-Border Transportation. A key to Unlock Full-Scale CCS*. In: *Energy Procedia*, pp. 7443–7458. 2017.

[KAL19] KALIS, M.: *Rechtsrahmen für ein H2-Teilnetz. Nukleus einer bundesweiten, öffentlichen Wasserstoffinfrastruktur*. – URL: https://www.ikem.de/wp-content/uploads/2019/10/Rechtsrahmen-f%C3%BCr-ein-H2-Teilnetz.pdf. 2019.

[KRI12] KRIEG, D.: *Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff*. Jülich: Forschungszentrum Jülich. 2012.

[MAH20] MAHGEREFTEH, H.; SPAN, R.; MOE, A. M. ET AL.: *A Trans-European CO2 Transportation Infrastructure for CCUS. Opportunities & Challenges*. – URL: https://zeroemissionsplatform.eu/a-trans-european-co2-transportation-infrastructure-for-ccus-opportunities-challenges/. 2020.

[MÜL13] MÜLLER-SYRING, G.; HENEL, M.; KÖPPEL, W. ET AL.: *Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz*. – URL: https://www.dvgw.de/medien/dvgw/forschung/berichte/g1_07_10.pdf. 2013.

[MÜL18] MÜLLER-SYRING, G.; HENEL, M.; POLTRUM, M. ET AL.: *Transformationspfade zur Treibhausgasneutralität der Gasnetze und Gasspeicher nach COP21. Abschlussbericht*. 2018.

[PET18] PETROV, K.; STEINBOM-CHENG, W.; FRANCESE, C. ET AL.: *Study on the Future Role of Gas from a Regulatory Perspective*. – URL: https://www.ceer.eu/documents/104400/-/-/6a6c72de-225a-b350-e30a-dd12bdf22378. 2018.

[RON20] RONNACKER, U.: *Rechtliche Herausforderungen bei der Umstellung von Gasbezugsquellen und Gasarten*. In: *Recht der Energiewirtschaft*, pp. 178–182. 2020.

[ROS20] ROSIN, P.; SPIEKERMANN, K.; BOURAZERI, K. ET AL.: *Leitungsgebundene Infrastruktur für Wasserstoff*. In: *Energiewirtschaftliche Tagesfragen* 70 No. 5, pp. 54–58. 2020.

[RYD15] RYDBERG, N.; LANGLET, D.: *CCS in the Baltic Sea Region. Legal & Fiscal Aspects*. – URL: https://www.globalccsinstitute.com/archive/hub/publications/190063/ccs-baltic-sea-region-bastor-2-work-package-4-legal-fiscal-aspects.pdf. 2015.

[SAD18] SADLER, D.; SOLGAARD ANDERSON, H.; SPERRINK, S. ET AL.: *H21 North of England. H21 NoE Report/2018*. – URL: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf. 2018.

[SIE20] SIEBERG, C.; CESARANO, C.: *Rechtsrahmen für eine Wasserstoffwirtschaft*. In: *Recht der Energiewirtschaft*, pp. 230–242. 2020.

[WAC19] WACHSMUTH, J.; DEGÜNTHER, C.; MICHAELIS, J. ET AL.: *Roadmap Gas für die Energiewende. Nachhaltiger Klimabeitrag des Gassektors*. – URL: https://www.umweltbundesamt.de/publikationen/roadmap-gas-fuer-die-energiewende-nachhaltiger. 2019.

5 SOCIOLOGICAL PERSPECTIVE AND RESULTS

5.1 Objective and State of Research

The research interest of the sociological study is to investigate the social perception of Carbon Capture and Storage (CCS) and hydrogen technologies to identify opportunities and risks of the three infrastructure options (see section 1.2) in terms of social acceptance. Social acceptance is a central factor for the successful implementation of new large-scale technologies, which also include energy technologies. Energy technologies usually go hand in hand with new large-scale infrastructure and thus mean a permanent intervention in the environment or a permanent change in the landscape, which in turn is associated with negative consequences, such as risks for the environment or a reduction in the quality of life. At the same time, energy technologies are often perceived as technologies that pose a major risk, especially in the case of an incident. Lack of social acceptance was one main reason for the rejection of planned and partly already started CCS projects in Germany (see e.g. [DÜT16]). Also the implementation of other energy projects, such as wind farms (see e.g. [REU16]) or transmission power lines (see e.g. [GAL18]), has shown lack of social acceptance and citizen protests which partly led to their abandonment.

In recent years, several studies on the acceptance and assessment of hydrogen and CCS technologies have been carried out. First acceptance studies on CCS technology were carried out between 2006 and 2014, related to planned or already abandoned CCS projects in Germany. These studies indicated rather little acceptance of CCS technologies, especially the storage of CO_2, in the German population. Yet, the level of awareness and knowledge of as well as familiarity with CCS technologies was found to be rather low [SCHU14; PIE11]. Nevertheless, as shown by the successful project implementation in Ketzin, there was no general nationwide refusal of CCS, but acceptance depended on several factors [DÜT15]. Dütschke et al. (2016) revealed in their analyses that people evaluated CCS in the context of industry processes or biomass more positive than in the context of coal-fired plants [DÜT16]. Braun et al. (2018) found the perceived seriousness of climate change, trust in institutions and whether CCS is perceived as a technology that defers responsibility or manipulates nature to be central factors of acceptance [BRA18]. Regarding different stakeholder groups, especially the government, industry and energy experts have a mainly neutral or positive attitude towards CCS while environmental NGOs are rather critical towards the technology [FIS09]. More recent data from 2017, comparing the public perception of CCS and carbon capture and utilisation (CCU), stated a general acceptance of CCS and CCU. But CCS is perceived less positive than CCU, mainly due to risks associated with storage and transport [ARN19].

Social acceptance of hydrogen technologies was analysed in several studies that have been performed in recent years. The German Federal Government’s National Innovation Programme Hydrogen and Fuel Cell Technology (NIP) was accompanied by the socio-scientific research projects HyTrust (2009-2013) and HyTrustPlus (2014-2016) to monitor social acceptance. Also, in further European countries studies were conducted to examine social acceptance of hydrogen fuel cells, hydrogen mobility and its infrastructure (e.g. hydrogen fuel stations). In these studies, hydrogen technologies have mostly been evaluated neutral to positive, while participants’ knowledge, familiarity and experience was rather low [ZIM12; ACH10; HEI08; HUI15]. Negative associations were linked to perceived costs rather than to potential risks of the technology [ZIM12]. Huijts et al. (2015) found the Dutch population to approve the implementation of hydrogen fuel stations, although this positive attitude was limited by a NIMBY effect (Not In My Back Yard). Besides, they found psychological variables to be more relevant for acceptance than socio-demographic or spatial variables [HUI15]. Nevertheless, Achterberg et al. (2010) found young and higher educated men to be the most supportive of hydrogen technologies in the Netherlands [ACH10]. Only few studies analysed the acceptance of hydrogen without focusing on one of the previously mentioned fields of application. Schmidt et al. (2016) found independence from central power grid and potential of decentralisation to be relevant factors for the acceptance of hydrogen. Their results also showed rather less concerns regarding hydrogen storage, while the statement that 'additional hydrogen pipelines are a good solution' was equally agreed and not agreed [SCH16a]. These acceptance studies on hydrogen technology indicate rather high acceptance of hydrogen technologies.

A research gap is left regarding acceptance of hydrogen technology related large-scale infrastructure, such as hydrogen pipelines. Even though hydrogen pipelines for industrial application already exist in Germany, their extent is not comparable with the needed pipeline infrastructure for hydrogen as part of future energy systems. Furthermore, the acceptance of H_2-CCS chains is not examined yet.

5.2 Theoretical Embedding

Energy technologies are shaped by their characteristic to come along with large-scale technology and infrastructure. Energy technologies are therefore classified as external technologies according to [REN97] which are met with a higher level of refusal than everyday technology or technology at work. This is above all ascribed to ambivalent perceptions considering risks and benefits and their distributive justice [SCH17a]. Based on knowledge, interests and values, controversial perceptions of risks and benefits are causing technology conflicts [REN97]. A central aspect in terms of acceptance of energy technologies is the frequent discrepancy between the acceptance of the technology in general and the acceptance of the related infrastructure. Therefore, the theoretical framework to analyse acceptance of H_2-CCS chains is a systematisation of acceptance, in which the authors differentiate between three levels of acceptance (see Table 5.1) [HIL18; FLA19].

1. The level of decarbonisation by H_2-CCS chains in the context of the energy transition concerns the general acceptance whether H_2-CCS chains are perceived as an adequate instrument of reducing CO_2 emissions. This acceptance strongly depends on available alternatives to reduce CO_2 emissions. Both ahead is the problem perception that CO_2 emissions need to be reduced is affecting acceptance.
2. The level of accepting the implementation and its consequences is going beyond the general acceptance and concerns the consequences that occur with the implementations of H_2-CCS chains. New infrastructure that comes along with the implementation is a main aspect of this level. The implementation level is differentiated between accepting consequences in general or in the own neighbourhood (NIMBY). Perceived benefits, risks and costs determine the acceptance of consequences.
3. Acceptance of procedures are the third level of acceptance and are linked to the implementation process of H_2-CCS chains. To gain public acceptance for procedures, they need to be perceived as fair. Besides, trust in stakeholders who are involved in the implementation process is a key element to raise acceptance of procedures.

Table 5.1: Systematisation of Acceptance based on [HIL18; HUI12; ZOE12].

Levels of Acceptance	**Factors of Acceptance**	**Range of Acceptance**
Acceptance of decarbonisation by CCS-H_2 chain as part of the energy transition	e.g. problem perception and available alternatives	Support Engagement Approval Indifference Toleration Rejection Resistance
Acceptance of the implementation and its consequences • In general • In the own neighbourhood (NIMBY)	e.g. perceived costs, risks and benefits	
Acceptance of procedures (communication, participation) and relevant stakeholder	e.g. fairness and trust	
Context e.g. knowledge, experience, socio-demographics, spatiality, values		

This systematisation enables to have a more differentiated view on acceptance and to identify critical moments of acceptance. Acceptance on the first level is required for acceptance on the second level. The second and third level are mutually dependent on each other: acceptance on the second level increases the probability of acceptance on the third level. However, acceptance on the third level has the potential to change acceptance on the second level – in a positive as well as in a negative way. The context, such as the knowledge on and experience with the technology as well as socio-structural characteristics, spatiality and values shape the acceptance on the different levels.

5.3 Research Design

A mixed-methods-design was applied to analyse social acceptance of the three H_2-CCS options. The research design consists of explorative qualitative stakeholder interviews and a quantitative population survey. First, qualitative stakeholder interviews were conducted to explore social objectives, interests and motivations. Stakeholders make themselves heard in order to assert and establish their views and interpretations, whereby they essentially shape and determine the public debate. Therefore, stakeholders are defined as multiplicators, which are crucial for the formation and progress of social debates on energy transition [REN97; LÜT12]. To cover the different social positions, stakeholders of the four societal subsystems politics, economy/industry, civil society and science or at intersections between the systems were identified (see Table 5.2). The systems have different functions, according to which the stakeholders act. The interviewed stakeholders were experts in at least one of the key issues 'CCS', 'hydrogen' or 'acceptance of energy infrastructure'. Interviews with energy companies and industry focused more on the technologies, while interviews with civil society stakeholders focused more on the social acceptance of the technology and infrastructure. In this way, a comprehensive view of positions and conflicts arising from decarbonising the gas infrastructure via hydrogen and CCS is obtained.

Table 5.2: Selected stakeholders and their function based on [REN97; FIS08; GLA20].

Societal Subsystems	*Stakeholders*	*Function*
Economy	Companies	Pursue economic interests; thematic positioning depends on economic interest
Politics	Political stakeholders	Decision makers; define the political and legal framework for energy and climate policy
Civil society	e.g. NGOs, civil associations	Represent public opinion
Science	e.g. universities, research institutions, institutions for knowledge transfer	Influence public opinion; dependent on public/private research funds
Interviews (N=10)	Representatives of Federal Ministry, Competence Centre for Energy, Hydrogen Organisation, Environmental Organisation, Association for technical professions, Industrial Association, Company for Energy Production, Company for Energy Transport, Company for Energy Storage.	

The interviews with the stakeholders (see Table 5.2) included the following topics:

- Evaluation of H_2-CCS technologies to decarbonise the energy system
- Experience with and evaluation of technology acceptance in society
- Experience with public participation during planning processes
- Information and communication needed to evaluate technologies

The interviewed stakeholders were assured of anonymity. The interviews were transcribed and analysed using the method of thematic coding. Based on theoretical considerations, categories were developed and further differentiated and adapted during the analysis [HOP95]. By applying a qualitative research method, the analysis of the interviews is inductive, flexible and data-driven with the aim to generate and develop descriptions, interpretations and explanations. Every argument is equally valued, independent of the frequency of its mention [HAM13].

Second, data on social acceptance of the three H_2-CCS options was gathered by a quantitative online survey, running in April 2019. The population were people living in Germany aged 15 and older, quoted by gender, education, age and federal state. For the survey, the online access panel from respondi AG was used, who also launched the survey. The adjusted data set was n=1438.

In order to establish comparability with previous research, the questionnaire was based on surveys already carried out (including [BES2009; DÜT16; HUI07; PIE11; SCH17b; TER13; WAL11]). The main part of the survey was an information-based evaluation[6] [BES09; TER13] of three different options regarding the decarbonisation of the German gas sector via hydrogen technologies and carbon capture and storage (CCS) in the context of the energy transition. The evaluation of each option was followed by questions regarding the acceptance of their implementation, focusing on pipeline infrastructure. Besides, data on general technology acceptance and acceptance of procedures and stakeholders as well as information on attitudes and values regarding environmental and energy issues were collected. Finally, the questionnaire included questions on socio-structural characteristics, such as socio-demographic, socio-economic and socio-cultural characteristics and the current living situation.

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[6] Attitudes and acceptance towards the technologies were measured, providing information on attributes that were needed to conceive well-considered and well-informed opinions. The authors took into account that the opinions are dependent on the provided information.

Each respondent had to evaluate one of the three different H_2-CCS options. Respondents evaluated either

(1) Option 1: decarbonisation of major CO_2 point sources in Germany and transport of CO_2 to the Netherlands to be stored offshore (n=458) or

(2) Option 2: decarbonisation of natural gas via CCS in Norway and gradual adaptation of the current natural gas infrastructure to hydrogen infrastructure in Germany (n=468) or

(3) Option 3: decarbonisation of natural gas via CCS in Norway and development of a new hydrogen infrastructure in Germany (n=512).

5.4 Qualitative Results: Evaluation from a Stakeholder Perspective

The stakeholder positions are assumed to represent dominant social perceptions and reflect chances and risks for acceptance. The results of the interviews indicate controversial as well as consensual perceptions of the H_2-CCS options (see Table 5.3). The positions of the stakeholders are presented in summary form below. A detailed elaboration of the results was published in [GLA20].

While pursuing the common goal of addressing climate change and reducing CO_2 emissions, the stakeholders formulate different requirements concerning the strategies towards a low-carbon society, especially the speed of phasing-out fossil energies. The assessment of H_2-CCS chains as an instrument to reduce CO_2 emissions in the context of the energy transition range from rejection to deeming it absolutely necessary. Argumentations behind these positions refer among others to economic feasibility, environmental protection, assumptions on dealing with societal demand and needs as well as security of energy supply with and without fossil energies. Thus, the evaluation of H_2-CCS chains represents central conflicts within the discourses on energy transition, identified by previous studies (e.g. in [LEI17; BUS19]): on the one hand, H_2-CCS chains are supposed to support the existing 'fossil' structures rather than creating a transition. It is criticised that economic factors are placed before environmental protection. On the other hand, H_2-CCS chains are supposed to enable a slower phasing-out of fossil energies. It is considered that a slow phasing-out is necessary to secure economic competitiveness and energy supply. This main conflict along environmental and economic consequences has already been found in previous studies [ZAU18; SCH17a].

Alongside opposing and conflicting arguments within and between the social areas of politics, economy/industry and society, there are also consensual perceptions and intersecting sets in evaluating H_2-CCS chains. A general openness to technologies is the more or less shared position of the stakeholders in the context of the energy transition. Especially the hydrogen part of the H_2-CCS chain represents a compatible element for all positions because it represents a link from fossil energies to the expansion of renewable energies. But consensual perceptions were identified in the CCS part of the chain, too. Albeit to varying degrees, all stakeholders acknowledged the general potential of reducing CO_2 emissions as opportunity and strength of H_2-CCS chains. The consensus must, however, be limited to the decarbonisation of industry-induced or bioenergy-induced emissions via CCS. The higher approval of CCS in the context of industry processes and biomass than in the context coal-fired plants was already found in studies on social acceptance [DÜT16]. On the infrastructural level, using existing infrastructure is preferred from an economic and ecological perspective.

Regarding the stakeholders' evaluation of social acceptance, it becomes apparent that the public is assumed to favour renewable energies as instruments to reduce CO_2 emissions. However, on the level of consequences, new infrastructure is assumed to be rejected in the context of renewable energies (green hydrogen) as well as in the context of fossil energies (natural gas, CO_2). Regarding acceptance of stakeholders, representatives of political and especially industrial/economic organisations perceive that they are less trusted than stakeholders from civil society, like environmental NGOs or consumer associations.

Table 5.3: Stakeholder perspective – consensus and conflicts [GLA20].

Level	***Consensus***	***Conflict***
Acceptance of H_2-CCS chains as part of the energy transition	• Achieving climate goals • Potential of CCS to reduce CO_2 emissions • CCS as a bridging technology • Decarbonisation of industry and BECCS • Potential of hydrogen, especially green hydrogen • Openness toward technologies	Controversial assessment of • strategy towards a low-carbon society • period of bridging technology/ phasing out fossil energies
	H_2-CCS chains are accepted under certain conditions. Conflicts run along economic and ecological arguments.	
Acceptance of implementation and its consequences	• Using existing infrastructure • Missing legal and political framework and acceptance for (new) infrastructure	Controversial assessment of • technical feasibility • ecological consequences • economic feasibility
	Main challenges are economic feasibility, legal/political feasibility, ecological consequences and social acceptance. The relevance and prioritization of challenges differ between stakeholder groups.	
Acceptance of procedures and relevant stakeholders	• High awareness that public has to be taken into account • Stakeholders are trusted to varying degrees	• Controversial perception of public participation in planning process
	Trust and credibility of stakeholders is essential for social acceptance, but stakeholders involved in implementation processes (investors) are often not the trusted ones.	

To conclude, the stakeholders from the sub-systems civil society, politics, economy/industry and science evaluate the options differently. Mainly ecological and economic arguments are opposed to each other and lead to different evaluations of the instruments with the same objective of reducing CO_2 emissions. However, there are also starting points to dissolve these opposed assessments. The compatibility of hydrogen technologies with renewable and fossil energies or the restriction of the use of CCS only for certain applications (industry, bioenergy) represent compromises which are supported by different stakeholder groups and which provide a balance of ecological and economic arguments. These consensual perceptions together with a general technology openness indicate chances to approach solutions for broad acceptance by stakeholders who are assumed to represent different social perspectives in the context of the energy transition. Furthermore, the awareness of considering the public in the course of planning processes is promising to increase acceptance on the level of implementation and procedures.

5.5 Quantitative Results: Evaluation by the Public

Quantitative data on social acceptance of the H_2-CCS options was gathered, to get insights from the general public and to verify the perspectives and positions identified in the explorative interviews. To quantitatively analyse the three infrastructure options in regard to social acceptance, an information-based questionnaire design was adapted (see section 5.3). After receiving expert-based information on one of the H_2-CCS options, the respondents were first asked to evaluate several consequences that come along with the option from positive to negative or unimportant. Secondly, the respondents were asked to evaluate risks, benefits, costs, and the future perspective of the option. Finally, they were asked to give an overall evaluation of the option. To control the quality of the answers, the respondents were asked, if they understood the expert-based information, how confident they were in their assessment and which information was missing for the evaluation.

The overall evaluation shows that most of the respondents evaluate the options rather positive. Around 30 percent in each option chose the middle category (partly/partly), which also reveals a high level of ambivalence. Furthermore, Option 1 receives significantly more negative ratings than Option 2 and Option 3 (see Figure 5.1).

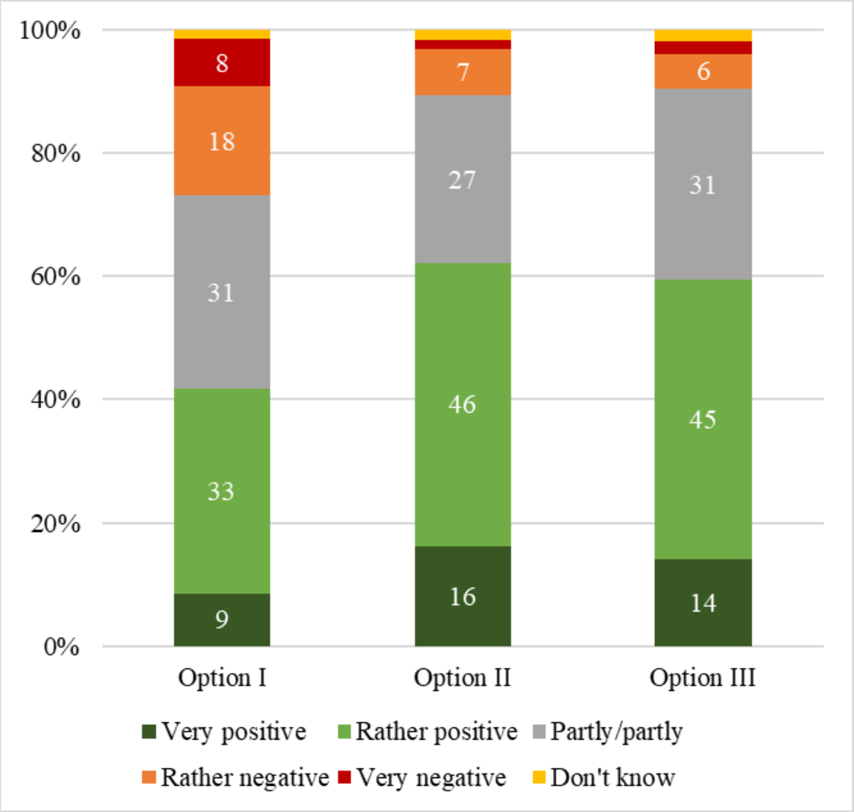

Figure 5.1: Assessment of scenario ("All in all, how do you assess the scenario?"; $n_{Option\ 1}$= 458; $n_{Option\ 2}$=468; $n_{Option\ 3}$=512).

The less positive evaluation of Option 1 compared to Option 2 and 3 is reflected in the evaluation of benefits, risks and costs of the options (see Figure 5.2 and Figure 5.3). The evaluation of Option 2 and Option 3 regarding these aspects is quite similar, while the evaluation for Option 1 is differing, but with same tendencies. The benefits of Option 1 are perceived lower than the benefits of Option 2 and 3. Benefits for climate, environment and Germany are evaluated the highest, benefits for future generations and for oneself are evaluated the lowest. While in Option 2 and 3, the benefit for environment and climate are evaluated as about the same, in Option 1, the benefit for the environment is evaluated slightly lower than the benefit for climate. This result indicates that in the assessment of CCS, a distinction is made between environment and climate. This may be because the environmental impact of CCS technologies is perceived as competing with the benefits for the climate. To achieve the positive effects for the climate, interventions in the environment are necessary. In the case of the Options 2 and 3, these effects may be offset by the combination with hydrogen. However, the average value being higher than three regarding all aspects of benefits reveals that the benefits are evaluated rather medium to high in all infrastructure options.

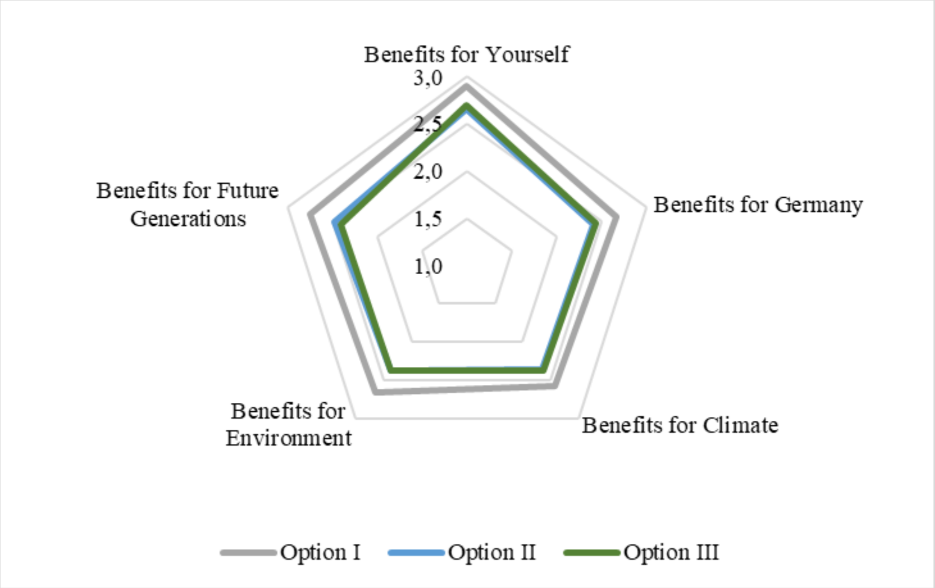

Figure 5.2: Evaluation of benefits ("How do you evaluate the overall benefits of the scenario for…?"; 1(very high) to 5(very low); n=1438).

The analysis of risk and cost evaluation of the options shows a partly complementary pattern to the benefit evaluation. Overall, risks and costs of Option 1 are evaluated higher than risks and costs of Option 2 and 3. The highest risks are assumed to occur for Germany, followed by risks for oneself. For Option 1, risks for future generations and the environment are assumed to be similarly high. In Option 2 and 3, these are assumed to be clearly lower. Costs arising from the options are assumed to be rather low for oneself and slightly higher for Germany.

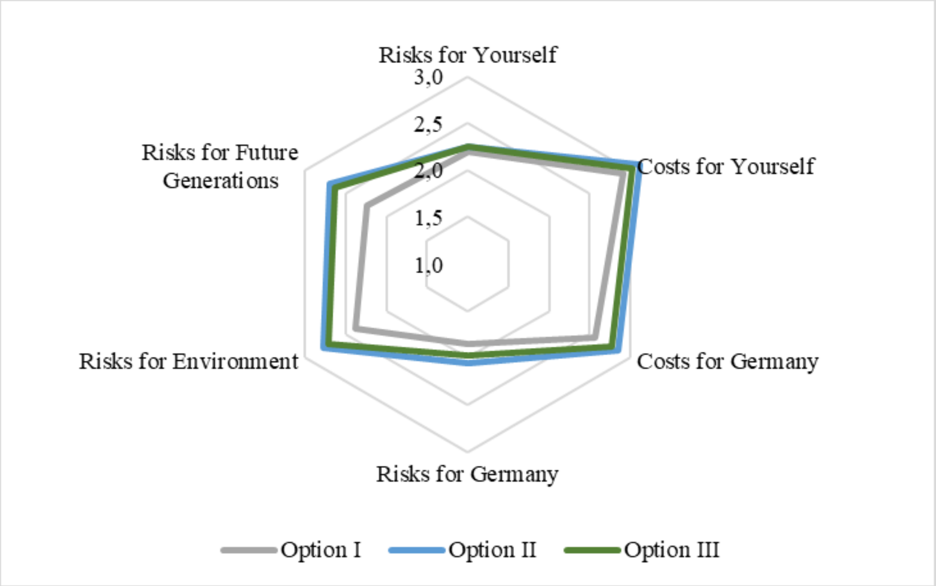

Figure 5.3: Evaluation of risks[7] and costs[8] of option; (1 (very high) to 5 (very low); n=1438).

The previous results of the overall evaluation show that the evaluation of the two H_2-CCS options – Option 2 and Option 3 – is quite similar, while there are differences to Option 1. Option 1 is the least positive evaluated option. Risks and costs are assumed to be higher and benefits lower than of Option 2 and 3.

5.5.1 Evaluation of Options along Value Chain

To understand where these differences come from and which variables are significant for the overall assessment, the evaluation of various consequences along the value chain is analysed separately for each option. It is assumed that a positive evaluation of the consequences leads to a positive overall evaluation and a negative evaluation of the items to a negative overall evaluation. The value chain of the technologies consists of CO_2 capture and hydrogen production, transport, storage and utilisation. Assumptions are derived from the current state of research as well as from the explorative results of the stakeholder interviews.

Regarding infrastructural consequences, the storage is assumed to have a strong influence on the overall evaluation: a negative evaluation of storage leads to a negative overall evaluation and vice

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[7] Option 1: “A possible risk is that a major accident (e.g. a leak) during transport or storage may release large quantities of CO2. Large quantities of released CO2 impede the oxygen uptake of living organisms and thus represent a risk for humans and the environment. However, CO2 is not explosive and non-toxic.”
Option 2: “A possible risk is that a major accident (e.g. a leak) during transport or storage may release large quantities of H2-natural gas-Mix. In this case, similar to natural gas, there is an increased risk of explosion. However, the H2-natural gas-MIX is non-toxic.”
Option 3: “A possible risk is that a major accident (e.g. a leak) during transport or storage may release large quantities of H2. In this case, similar to natural gas, there is an increased risk of explosion. However, H2 is non-toxic.”
All options: “The frequency and severity of risks are comparable to those of natural gas transport. Natural gas pipelines with a total length of over 500,000 km currently exist in Germany.
Pipelines and storage facilities have defined standards in Germany. Safety and emergency plans must be in place and detailed monitoring and inspection must be carried out in accordance with prescribed procedures.”
How do you evaluate the risk of the scenario?”

[8] All options: “The implementation of the scenario is linked to costs that will most likely lead to rising energy prices, both for private and industrial customers. How do you evaluate the costs of the scenario for...”

versa. The storage of CO_2 is assumed to be evaluated more negative than the storage of hydrogen. CO_2 storage is expected to be more accepted if the storage site is farer away from Germany.

The transport is expected to also have a strong influence. A pipeline to transport CO_2 is assumed to be evaluated more negative than a pipeline to transport hydrogen or a hydrogen/natural gas mix. Since new infrastructure encounters acceptance problems, it is assumed that measures with no or little infrastructural consequences will be assessed more positively. Accordingly, transport via ship is assumed to be evaluated more positive than transport via pipeline if the pipeline has to be newly constructed. Retrofitting pipelines is assumed to be evaluated more positive than building new ones.

The CO_2 capture process and its infrastructural consequences are assumed to have a low effect on the overall evaluation. However, the acceptance is expected to be higher for the application to decarbonise industry than to decarbonise coal-fired plants.

H_2 technologies are assumed to be evaluated more positively than CCS technologies. Due to the positive perception of hydrogen technologies, high acceptance is expected for the production hydrogen, but with a low impact on the overall evaluation.

5.5.1.1 Option 1

The descriptive analysis of the consequences (see Figure 5.4) reveals a rather balanced picture of 30 to 40 percent positive evaluations as well as of ambivalent evaluations. The number of negative evaluations is lower regarding most of the items.

Capturing CO_2 at industry or coal power plants both is evaluated positively by around 40 percent. Due to the negative perception of the energy carriers black coal and lignite in Germany, it is rather surprising that the capture of CO_2 at coal power plants is evaluated positively by as many people as the capture of CO_2 at industrial plants. However, the number of negative evaluations is higher for decarbonising coal power plants than for decarbonising industry.

The transport of CO_2 via pipelines is evaluated positively by around 40 percent. Even construction sites for the construction of pipelines are evaluated positively, negatively, and neutral by equal numbers of people. In contrast, transport by ship is predominantly assessed negatively. This results contradicts the assumption that consequences with high infrastructural impact are less accepted than those with no or less infrastructural impact and could be due to the fact that transport by ship is associated with additional CO_2 emissions. Although transport by ship may be easier to implement as it is initially less visible and noticeable than the construction of a new pipeline, transport by pipeline is the preferred way according to the survey results.

Storage of CO_2 offshore in the Netherlands is evaluated positively by 37 percent and thus comparable with the other aspects of the value chain.

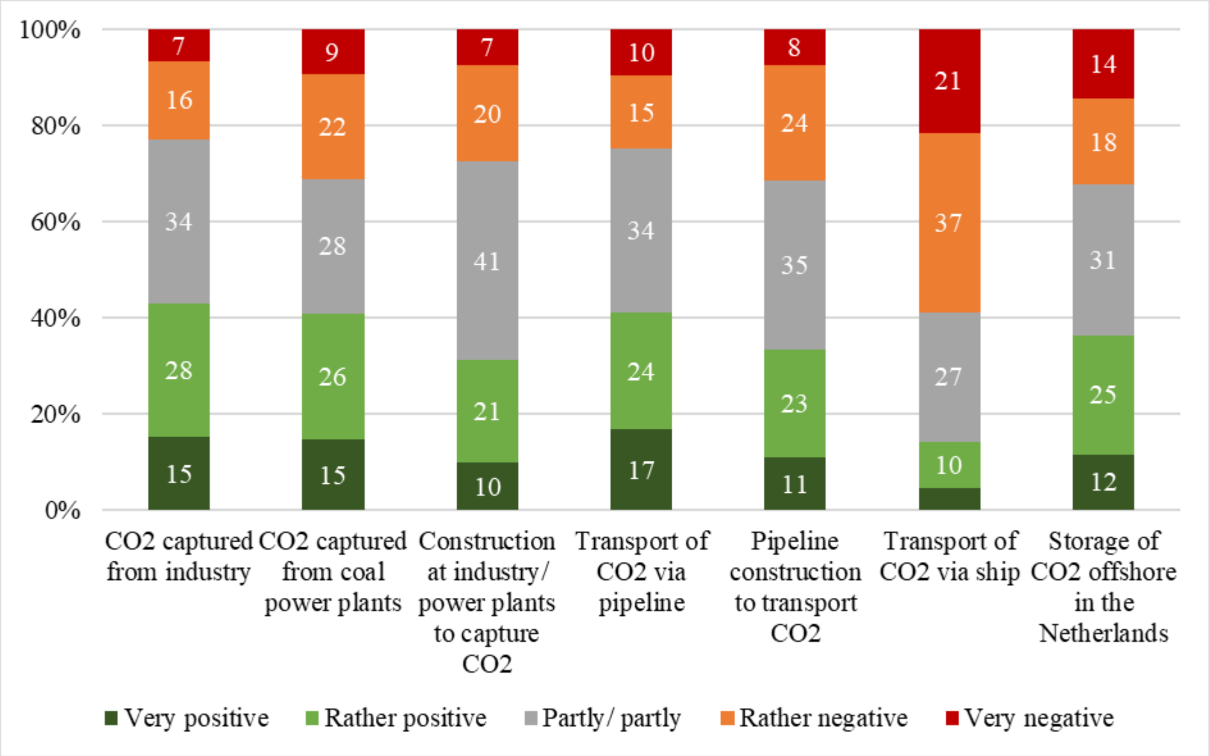


Figure 5.4: Descriptive analysis of the consequences of Option 1 ("The following aspects concern the framework conditions of the scenario. Do you evaluate these as positive, negative or unimportant?"; n=458; the category 'unimportant' was chosen by 4 to 8 respondents).

Table 5.4 shows the effects of infrastructural consequences on the overall evaluation of Option 1. The storage of CO_2 offshore in the Netherlands has the strongest effect on the overall evaluation, followed by the pipeline construction to transport CO_2. Besides, CO_2 captured from industry and transport of CO_2 via pipeline have significant effects on the overall evaluation. As assumed, aspects of storage and transport are important factors for evaluating CCS technology. Contrary to what was assumed, transport via ship has no significant effect on the overall evaluation. Regarding the application of CCS, capturing CO_2 from industry has a positive effect on the overall evaluation, while capturing CO_2 from coal power plants has no effect.

Table 5.4: Effect of consequences on Option 1 (n=436).

	b	**b***	**Sign.**
Effects			
CO_2 captured from industry	.137	.144	**
CO_2 captured from coal power plants	-.012	-.013	
Transport of CO_2 via pipeline	.108	.120	**
Transport of CO_2 via ship	.015	.015	
Storage of CO_2 offshore in the Netherlands	.286	.325	***
Pipeline construction to transport CO_2	.209	.216	***
Construction at industry/power plants to capture CO_2	.016	.015	
R= 0,667			
R^2=0,444			

***0,001; **0,05

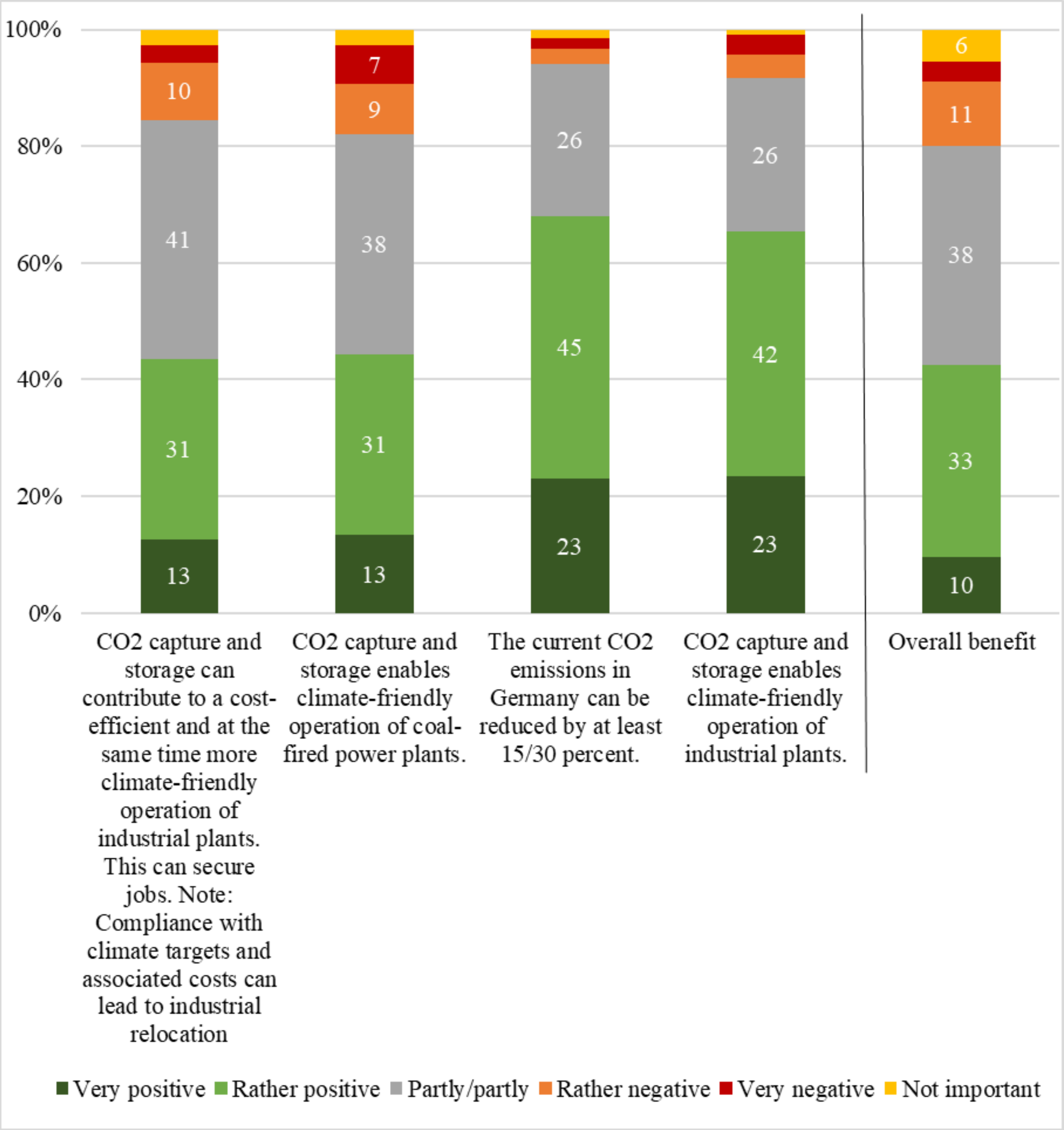


Figure 5.5: Specific Benefits of Option 1 ("The following aspects are defined as benefits of the scenario. Do you rate them as positive, negative or unimportant?"; n=458).

The possibility to reduce CO_2 emissions as well as the possibility to enable climate-friendly operations of industrial plants are mostly evaluated as positive (see Figure 5.5). The climate-friendly use of coal power plants and securing jobs are evaluated positive by more than 40 percent. However, the number is equal to ambivalent respondents. The strongest benefit is referred to the climate-friendly operation of industrial plants (see Table 5.5). The reduction of CO_2 emissions and the climate-friendly operation of coal power plants have weaker significant effects on the overall benefit. Contrary to the variables concerning climate protection, the variable 'securing industrial jobs' has no significant effect. This is possibly because the general benefit of the option is framed by climate issues and is therefore not linked to more economic/labour market components.

Table 5.5: Effect of specific benefit items on overall benefit (n=418).

	b	**b***	**Sign.**
Effects			
Reduction of CO_2 emissions by 15/30 %	.147	.138	**
Climate-friendly operation of industrial plants	.305	.307	***
Climate-friendly operation of coal power plants	.112	.127	**
Securing industrial jobs	.073	.075	
R=0,551 R^2=0,303			

***0,001; **0,05

All in all, Option 1 and its consequences are evaluated neutral to positive. CO_2 storage and CO_2 pipeline construction are the consequences that dominate the overall evaluation. The perception of climate-friendly operation of industrial plants mainly defines the overall benefit.

5.5.1.2 Option 2

The evaluation of the consequences of Option 2 shows a similar pattern as in Option 1, but with a higher number of positive evaluations (see Figure 5.6). 40 to 60 percent of respondents evaluate the consequences positively, 30 to 40 percent neutral and 10 to 20 percent negatively.

The production of hydrogen from natural gas is the most positive evaluated aspect, whereas capturing CO_2 from natural gas is evaluated clearly less positive. This result is in line with the assumption that hydrogen and hydrogen technologies are perceived positively and CCS technologies are perceived more skeptical, especially in combination with fossil energies.

Also, consequences related to the transport of the H_2/natural gas mix are mostly evaluated positively. The use of existing transport infrastructure may be a decisive advantage of the option in terms of acceptance.

The most negative aspect is the storage of CO_2 offshore in Norway. However, with 20 percent of negative responses it is evaluated less negative than the CO_2 offshore storage in the Netherlands in Option 1. The storage of hydrogen in existing underground storage sites is evaluated more positive by comparison. Again, the more positive assessment of hydrogen technologies compared to CCS technologies is evident.

Lastly, on the level of utilisation, the necessary exchange of heating burners to use hydrogen as an energy carrier, is evaluated least positive. This could be due to direct consequences for households and consumers which emerge from this aspect.

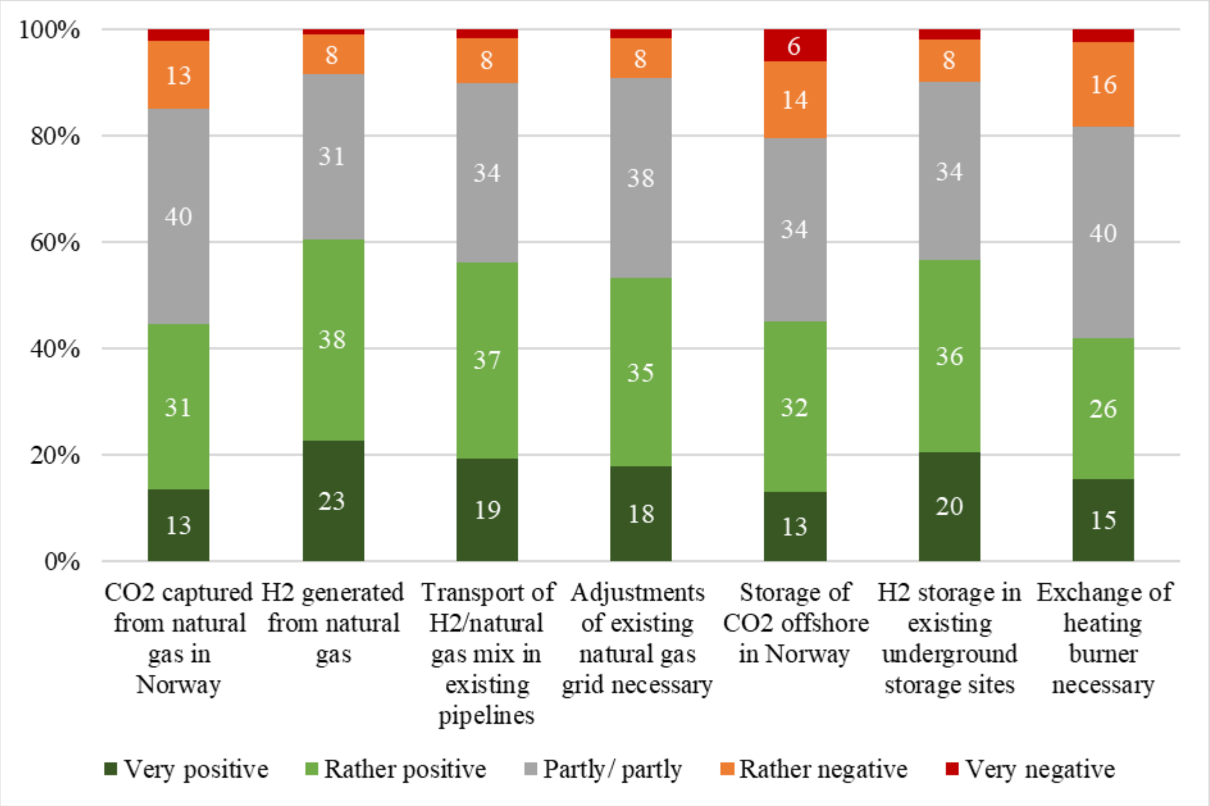


Figure 5.6: Descriptive analysis of the consequences of Option 2 ("The following aspects concern the framework conditions of the scenario. Do you evaluate these as positive, negative or unimportant?"; n=468; the category 'unimportant' was chosen by 2 to 4 respondents and is not shown in the figure).

As in Option 1, storage of CO_2 has the strongest effect on the overall evaluation of Option 2 (see Table 5.6). The storage of hydrogen has a significant effect on the overall evaluation as well. Further significant effects concern the exchange of heating burners and retrofitting the natural gas grid. CO_2 capture, production of H_2 and transport in existing pipelines have no or only weak effects on the overall evaluation. These effects may be explained because the storing CO_2 respectively H_2, retrofitting the gas grid and exchanging heating burners are linked with certain ideas and therefore are less abstract than capturing CO_2 or producing hydrogen.

Table 5.6: Effect of consequences on Option 2 (n=448).

	b	**b***	**Sign.**
Effects			
CO_2 captured from natural gas in Norway	.081	.089	
H_2 generated from natural gas	.087	.092	**
CO_2 storage offshore in Norway	.202	.246	***
Transport in existing pipelines	.052	.056	
Exchange of burner necessary	.114	.130	**
H_2 storage in existing spaces possible	.163	.177	***
For amount of H_2, retrofitting of existing natural gas grid necessary	.101	.107	**
R= 0,675			
R^2=0,456			

***0,001; **0,05

Around 75 percent evaluate the benefit to reduce CO_2 emissions positively (see Figure 5.7). Around 70 percent evaluate the climate-friendly use of natural gas as positive. This assessment shows that the climate-friendly potential of Option 2 is perceived particularly beneficial.

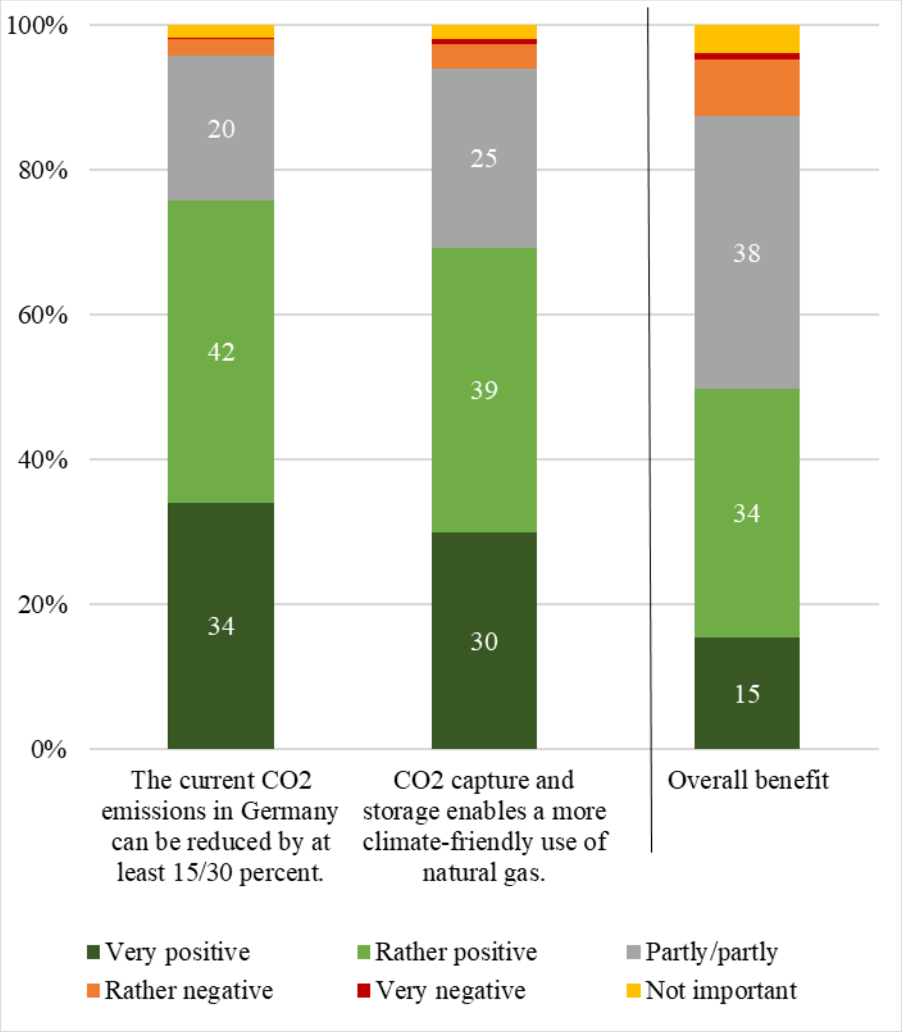


Figure 5.7: Specific benefits of Option 2 ("The following aspects are defined as benefits of the scenario. Do you rate them as positive, negative or unimportant?"; n=468).

The climate-friendly use of natural gas has a stronger positive effect on the overall benefit of Option 2 than the reduction of CO_2 emissions by 15 or 30 percent (see Table 5.7). People who rate the benefit of climate-friendly natural gas positively, rate the overall benefit of Option 2 positively. In return, people who do not see the benefits of climate-friendly natural gas, rate the overall benefit of the option less highly.

Table 5.7 Effect of specific benefit items on overall benefit (n=446).

	b	**b***	**Sign.**
Effects			
Reduction of CO_2 emissions by 15/30 %	.230	.211	***
Climate-friendly use of natural gas	.378	.376	***
R=0,549 R^2=0,301			

***0,001; **0,05

Option 2 and its consequences are evaluated rather positively and more positive than Option 1. As in Option 1, CO_2 storage dominates the overall evaluation, next to H_2 storage and consequences for the heating system. The overall benefit is mainly determined by the perception of using climate-friendly natural gas.

5.5.1.3 Option 3

The evaluation of consequences of Option 3 reveals similarities to Option 1 and Option 2. Positive evaluations vary from 18 to more than 60 percent; 30 to 40 percent of the respondents have ambivalent attitudes (see Figure 5.8).

Hydrogen production has the highest positive evaluation with more than 60 percent. As in Option 2, capturing CO_2 from natural gas is evaluated less positive.

As in Option 1, the transport via pipeline is clearly preferred to the transport via trucks. Even the necessary constructions to build new pipelines are perceived rather positively. Again, this may be since transport via pipeline – once it is constructed – has less impact on the environment (CO_2 emissions, noise etc.).

Storage of CO_2 offshore in Norway is – except transport by truck – evaluated least positive with around 40 percent approval, 21 percent rejection and 35 percent ambivalence. As in Option 2, H_2 storage is evaluated more positive than CO_2 storage, especially storage in existing underground storage sites. Overground storage sites is evaluated slightly less positive.

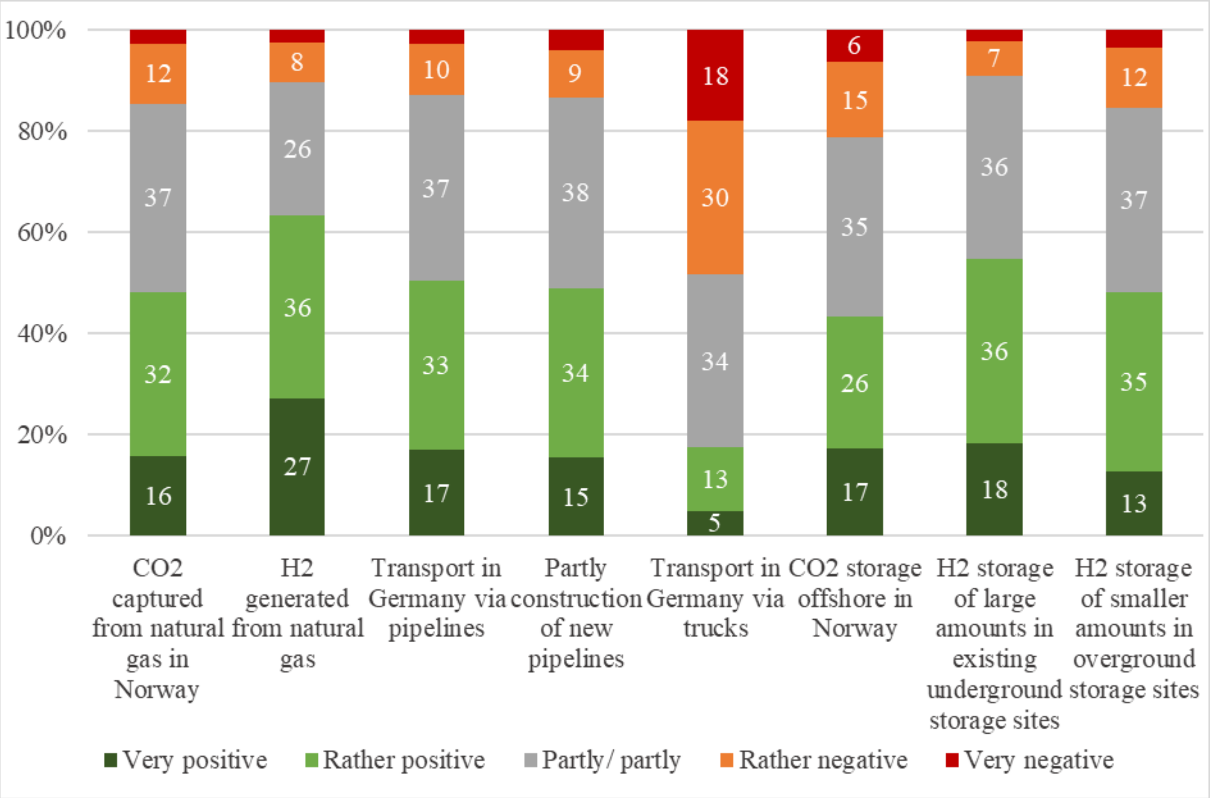


Figure 5.8: Descriptive analysis of the consequences of Option 3 ("The following aspects concern the framework conditions of the scenario. Do you evaluate these as positive, negative or unimportant?"; n=512; the category 'unimportant' was chosen by 3 to 8 respondents and is not shown in the figure).

As shown in Table 5.8 storage of CO_2 has the strongest effect on the overall evaluation. However, storage of H_2 in underground or overground storage sites also has relevant effects on the overall evaluation. The more positive storage is perceived, the more positive is the overall evaluation and vice versa. As in Option 1 and 2, storage is the main aspect to determine the perception. Transport of hydrogen via pipeline shows an effect as well, while the negative evaluated transport via truck is not relevant for the overall evaluation.

Table 5.8: Effect of consequences on Option 3 (n=485).

	b	**b***	**Sign.**
Effects			
CO_2 captured from natural gas in Norway	.046	.052	
H_2 generated from natural gas	.039	.046	
CO_2 storage offshore in Norway	.186	.239	***
Transport in Germany with pipelines	.157	.180	***
Transport in Germany with trucks	-.037	-.047	
Partly construction of new pipeline	.068	.078	
Large amounts H_2 storage in existing underground spaces	.172	.184	***
Smaller amounts H_2 storage overground	.097	.110	**
R= 0,688			
R^2=0,474			

***0,001; **0,05

Especially the benefits of using hydrogen as a carbon-free and therefore climate-friendly energy carrier and reducing the current CO_2 emissions by at least 15 or 30 percent are perceived positively by the respondents (see Figure 5.9). More climate-friendly use of natural gas through CCS is as well perceived positive by 68 percent. This distribution is remarkably similar to Option 2.

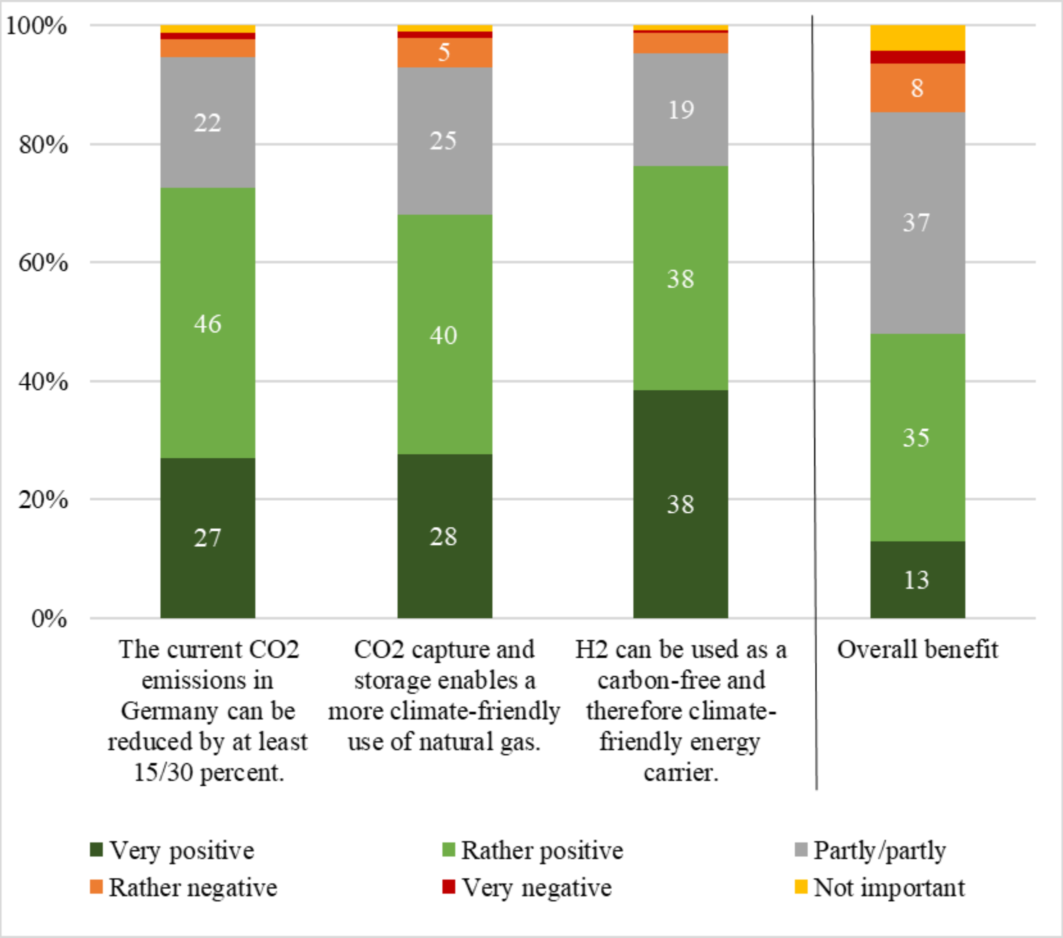


Figure 5.9: Specific benefits of Option 3 ("The following aspects are defined as benefits of the scenario. Do you rate them as positive, negative or unimportant?"; n=512).

As in Option 2, the climate friendly use of natural gas has the strongest effect on the evaluation of the overall benefits (see Table 5.9). The assessment of the overall benefits of Option 3 depends most on whether people value the climate-friendly use of natural gas positively or negatively.

Table 5.9: Effect of specific benefit items on overall benefit (n=490).

	b	b*	Sign.
Effects			
Reduction of CO_2 emissions by 15/30 %	.232	.224	***
Climate-friendly use of natural gas	.245	.253	***
H_2 climate-friendly energy carrier	.148	.147	**
R=0,564			
R^2=0,318			

***0,001; **0,05

To summarise, Option 3 is evaluated similarly positive as Option 2. Again, storage of CO_2 and H_2 has the strongest influence on the overall evaluation and climate-friendly natural gas the strongest influence on the overall benefit.

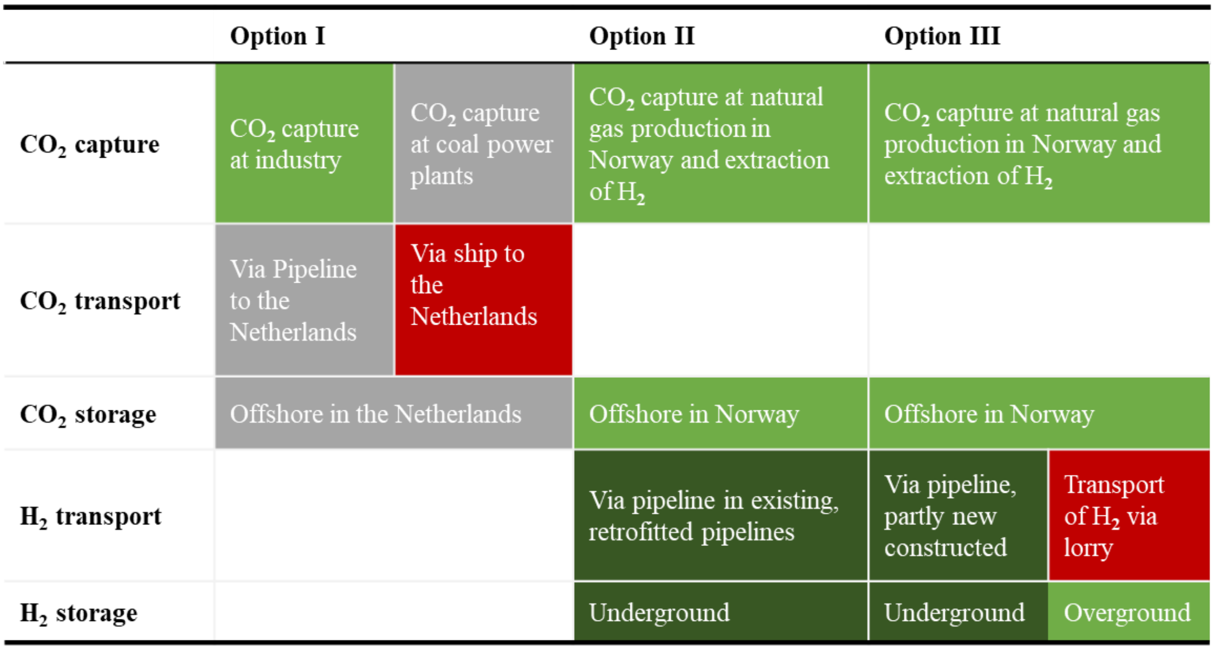
5.5.1.4 Conclusion of Options

The options are evaluated rather neutral to positive, but some aspects of the options are assessed more positive than others and some aspects are perceived rather negatively. Table 5.10

summarizes these assessments and illustrates which consequences appear to be chances based on the respondents' assessment and which aspects pose greater challenges in terms of acceptance.

The positively assessed aspects concern the capture of CO_2, the transport of hydrogen and its storage. Rated positively and negatively by about the same number of people are especially aspects of Option 1 – CO_2 capture at coal-fired power plants, transport of CO_2 by pipeline and CO_2 storage in the Netherlands. Only the transport of CO_2 by ship and the transport of hydrogen by truck were assessed clearly negative. In contrast to transport via pipelines, transport via ferry or lorry are measures without infrastructural adjustments. Therefore, the potential of protest may be lower than for pipeline constructions as it is initially less visible and noticeable. Depending on the extent, increasing traffic and consequently increasing air pollution and traffic noise may as well lead to protests.

Concluding, aspects of CCS technologies are perceived more sceptical than aspects of hydrogen technologies. Furthermore, CCS technology is assessed more positively, if it is applied further away from one’s home or if it is framed with hydrogen technology.



	Option I		Option II	Option III	
CO_2 capture	CO_2 capture at industry	CO_2 capture at coal power plants	CO_2 capture at natural gas production in Norway and extraction of H_2	CO_2 capture at natural gas production in Norway and extraction of H_2	
CO_2 transport	Via Pipeline to the Netherlands	Via ship to the Netherlands			
CO_2 storage	Offshore in the Netherlands		Offshore in Norway	Offshore in Norway	
H_2 transport			Via pipeline in existing, retrofitted pipelines	Via pipeline, partly new constructed	Transport of H_2 via lorry
H_2 storage			Underground	Underground	Overground

Figure 5.10: Positive (green;), neutral (grey) and negative (red) evaluated aspects of options.

5.5.2 Knowledge and Technology Acceptance

To interpret the evaluation of the H_2-CCS options, the separate evaluation of the technologies is of high relevance. As it is known from previous research studies (see section 5.1), CCS technologies are perceived rather sceptical, while hydrogen technologies are perceived rather positively. Knowledge is an important factor to evaluate technology, although more knowledge does not necessarily lead to more acceptance [BRU13]. According to the current state of research, there is little knowledge and familiarity with these technologies among lay people [DÜT15; HYA17; ZIM12; ACH10].

The data of our survey confirms these results (see Figure 5.11). Most respondents heard of hydrogen as an energy carrier, but do not know much about it. Only about 10 percent of respondents state that they know a lot about hydrogen as an energy carrier. Overall, the results reveal a rather high awareness of (the existence of) hydrogen (technologies), but a low level of self-assessed knowledge.

Contrary to hydrogen technologies, most respondents have never heard of CCS technologies (55.5 %) before the survey. Around 40 percent of the respondents heard of it, but do not know a lot about it and only about 4 percent of respondents claim to know much about the technology. Overall, the level of knowledge on CCS is very small, while there is partly awareness of the technology and partly no awareness at all.

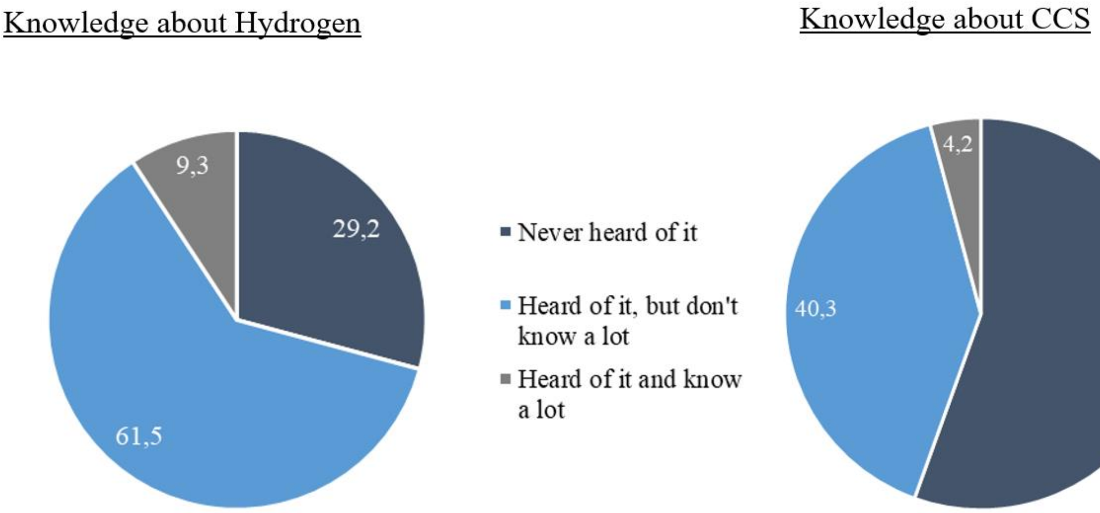


Figure 5.11: "Before this survey, have you ever heard of hydrogen as an energy carrier (e.g. in transport, for heat, in industry)?" (n=980)/ "Before this survey, have you ever heard of CO_2 *capture and storage (CCS)?" (n=1438).*

5.5.2.1 Assessment of Hydrogen

Using hydrogen as an energy carrier is perceived as positive and innovative by the respondents (see Figure 5.12). The most critical aspect regarding hydrogen concerns security with 14 percent of respondents evaluating hydrogen as risky and 45 percent of ambivalent respondents. Nevertheless, across all three items, the number of respondents evaluating hydrogen as positive, innovative and secure significantly exceeds the number of respondents evaluating hydrogen as negative, reactionary and risky.

People who claim to know a lot about hydrogen rate it more positively. Half of them rate it the most positive. People who have heard of it rate the energy carrier somewhat more cautiously, but also predominantly positive. People who have never heard of it rate the technology neutrally (40%) to positively. The same pattern can be seen in the evaluation of the innovation potential. Regarding risk assessment, knowledge has the clearest effect. 57 percent of the respondents who know a lot about hydrogen rate it as very or rather safe. For those who have heard of it, this figure is 45 percent. Only 27 percent of those who have never heard of it, rate it as safe, while 60 percent locate themselves in the middle. More knowledge therefore seems to minimize the perception of the technology as risky.

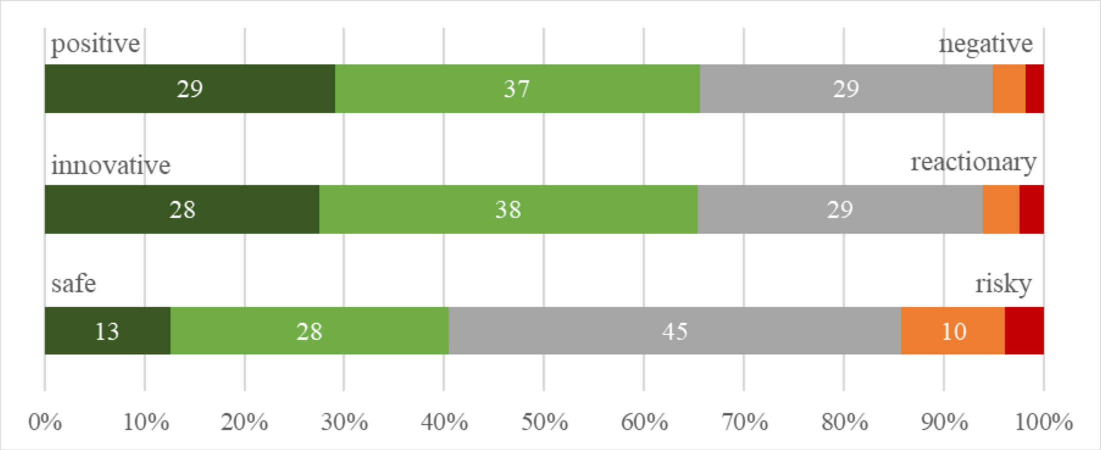


Figure 5.12: Evaluation of hydrogen (”After everything you know now: How do you evaluate the use of hydrogen as an energy carrier, e.g. for heat, in transport or in industry?”; n=980).

5.5.2.2 Assessment of CCS

Carbon capture and storage is evaluated as positive or negative by about 25 to 30 percent of respondents (see Figure 5.13). Nearly half of the respondents are ambivalent. The main part of the respondents evaluates the level of innovation as high. The evaluation of security versus risks of the technology is similar to that of hydrogen: around 30 percent evaluate CCS as secure, 20 percent as risky and 38 percent are ambivalent. It is interesting to note that the technology is valued differently depending on the option. Respondents who assessed the first option rated CCS technology as less positive, less innovative and less safe than respondents of the other two options. Also, in the evaluation of CCS technologies, an influence of knowledge on the evaluation is evident. People who claim to know a lot about the technology show very different patterns of perception: about 43 percent evaluate the technology positively and innovatively, 38 percent negatively and 31 percent reactionary. When assessing the risk, about 36 percent each rate the technology as safe or risky. Persons who state little or no knowledge show a very homogenous assessment pattern. They rate the technology predominantly neutral to positive. Only when assessing the risk do people without knowledge rate the technology as neutral to risky, while people with little knowledge rate the technology as neutral to safe. Overall, no linear relationship between knowledge and the evaluation can be established for CCS technologies. More knowledge tends to lead to clearer evaluations, but in both directions.

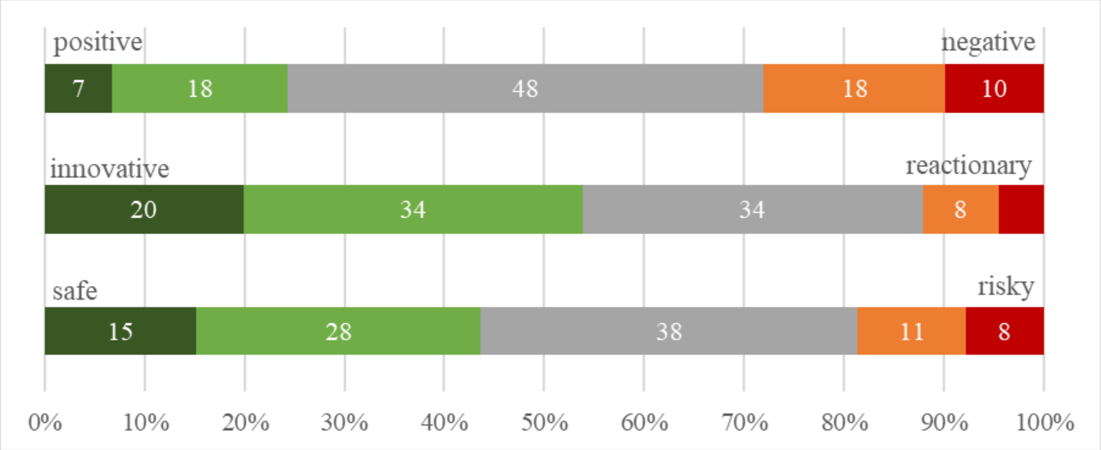


Figure 5.13: Evaluation of CCS (“After everything you know now: How do you evaluate capture and storage of CO_2?”; n=1438).

5.5.2.3 Assessment of Further Energy Carriers and Technologies

To classify the assessments of hydrogen technologies and CCS technologies, it is helpful to compare them with the assessment of other energy sources and technologies (see Figure 5.14). Furthermore, the acceptance of different energy carriers needs to be considered when analysing the acceptance of decarbonising fossil energies.

When asking for energy sources that should primarily be used to cover future energy needs by 2050, renewable energy systems are by far the most preferred ones with more than 80 percent preferring solar energy and nearly 80 percent preferring wind and hydro power. Nevertheless, among fossil energies, it is natural gas which is the one with the highest approval with 23 percent. This is consistent with the positive assessments of the Options 2 and 3 in which CCS is applied to decarbonise natural gas.

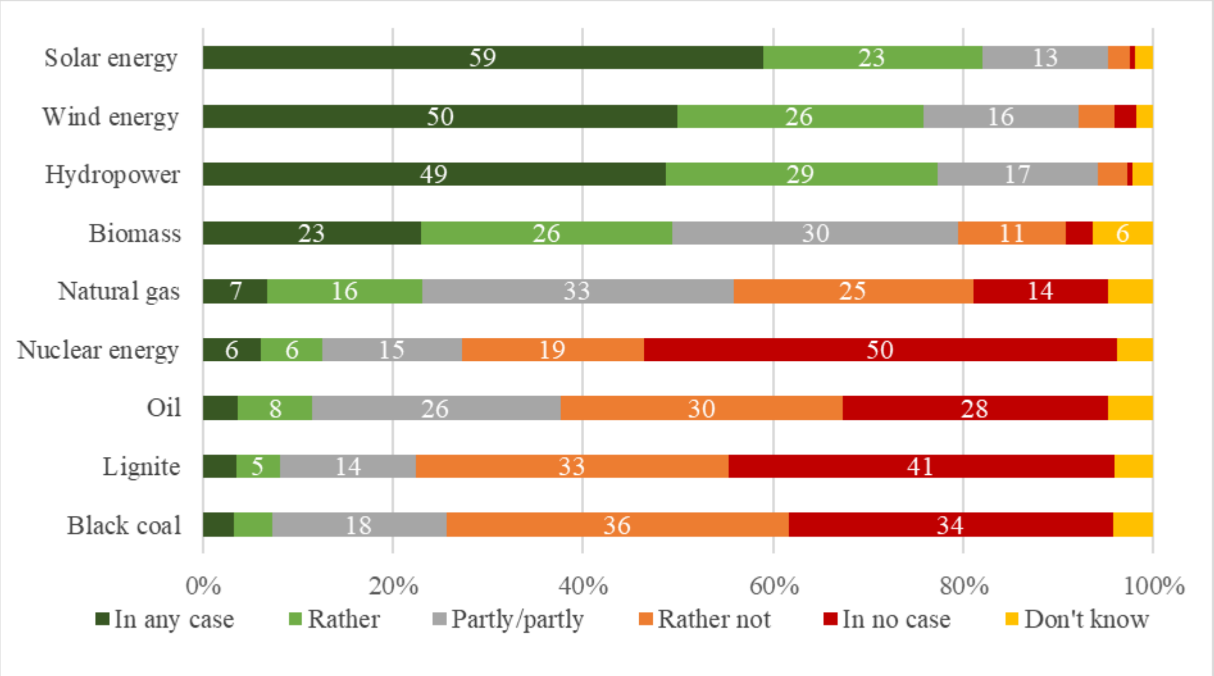


Figure 5.14: Acceptance of energy sources ("In your opinion, which of the following energy sources should Germany primarily use to cover its future energy needs by 2050?"; n=1438).

This preference for renewable energies is reflected in the preferred approach to reduce CO_2 emissions (see Figure 5.15). Renewable energy and energy efficiency are the most preferred instruments to reduce CO_2 emissions. The low acceptance of nuclear energy has a long tradition in Germany, which is one reason for the phase-out by 2021 [REN16]. The evaluation of carbon capture and storage (CCS) as an approach to reduce CO_2 emissions is quite interesting: before getting any information about the technology, the responses show a high rate of don't knows and nearly half of the respondents give a negative assessment. The assessment is becoming less negative and more ambivalent after receiving information and with having the possibility of a five-point scale to position oneself in the middle (see Figure 5.13). While the approaches energy efficiency, renewable energy, CCS and nuclear energy do not necessarily lead to changing energy behaviour, sufficiency does. This may be the reason for the more sceptical, but still positive assessment of this approach.

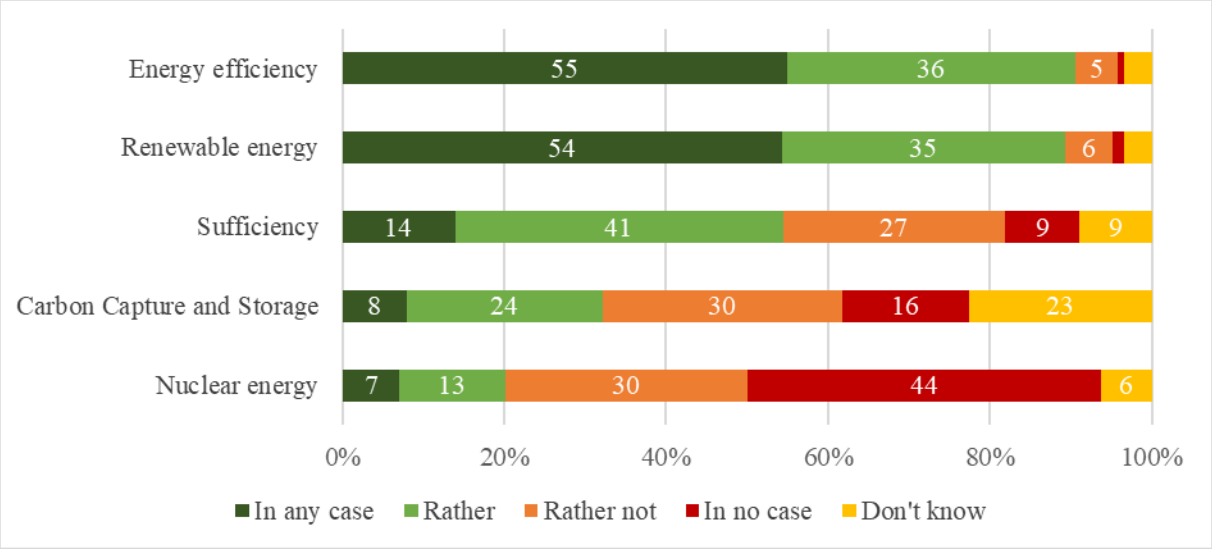


Figure 5.15: Approaches for CO_2 reduction ("There are various approaches to reduce CO_2 emissions in the context of the energy transition. If you had to create a plan to reduce CO_2 emissions, which of the following approaches would you use?"; n=1438).

The preference for renewable energies to reduce CO_2 emissions illustrates the potential of (green) hydrogen as a future energy carrier. Nevertheless, the positive assessment of natural gas as a fossil fuel also shows that the decarbonisation of natural gas, as planned in Options 2 and 3, represents feasible scenarios in terms of acceptance.

5.5.3 Acceptance of Implementation: Pipeline Infrastructure and NIMBY

Main infrastructural consequence of the three options is the construction of new pipelines or retrofitting existing pipelines. The analyses of the options revealed a rather high acceptance of pipeline infrastructure to transport CO_2 (Option 1), a hydrogen/natural gas mix (Option 2) or hydrogen (Option 3). Pipeline infrastructure is even more positively evaluated than transport via ferry (Option 1) or lorry (Option 3). Nevertheless, new or retrofitted pipelines need infrastructural adjustments and therefore have a high potential for protests. To analyse this potential, respondents were asked to imagine a pipeline construction close to their home for the transport of CO_2, a hydrogen/natural gas mix or hydrogen.

Regarding the pipeline infrastructure in the own neighbourhood, acceptance of Option 2 and Option 3 is similar, while Option 1 is differing. In Option 1 (new pipeline to transport CO_2), almost 40 percent of the respondents would be against the construction of a CO_2 pipeline, 40 percent would resign to it and 30 percent would approve it (see Figure 5.16).

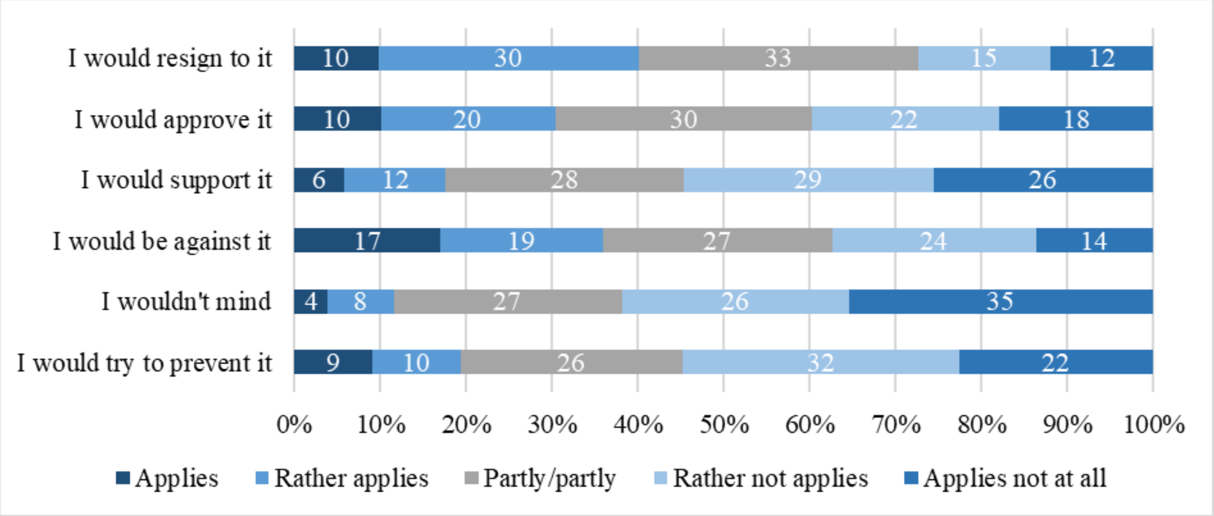


Figure 5.16: Option 1: Acceptance of CO_2 *pipeline ("Imagine for now, a pipeline is to be built near your home for the transport of* CO_2*. Would you accept the building project?"; n=458).*

In Option 2 (retrofit existing pipeline to transport H_2/natural gas mix), around half of the respondents would approve the pipeline. Nearly half of the respondents would resign to it and only around 20 percent would be against it (see Figure 5.17).

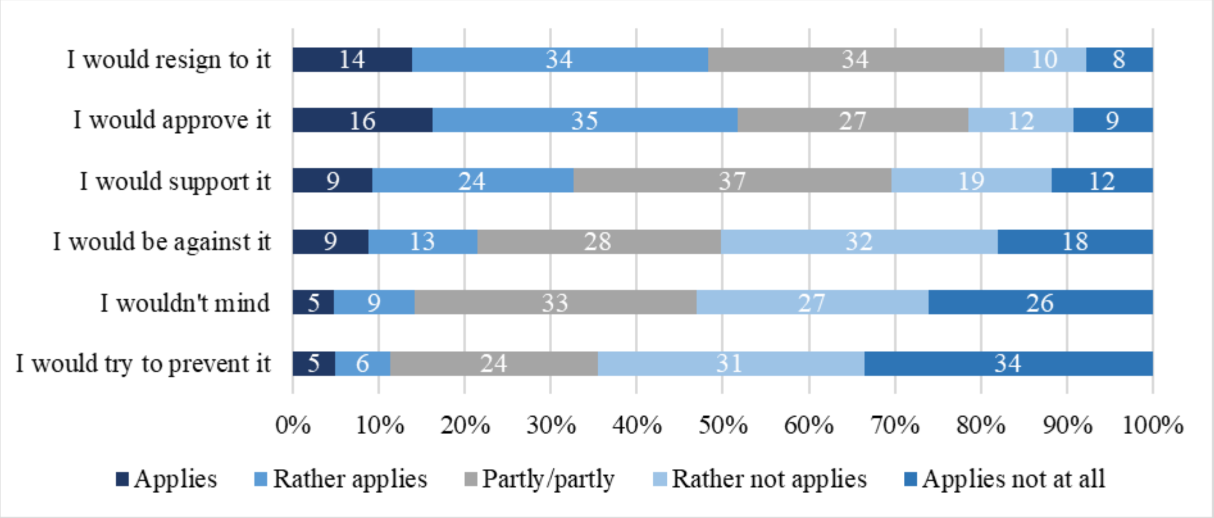


Figure 5.17: Option 2: Acceptance of H_2 */natural gas mix pipeline ("Imagine for now, a pipeline is retrofitted near your home for the transport of a* H_2*/natural gas mix. Would you accept the building project?"; n=468).*

In Option 3 (new pipeline to transport hydrogen), around half of the respondents would resign to a new hydrogen pipeline. A bit less would approve it (44 %) and around a quarter of the respondents would be against it (see Figure 5.18).

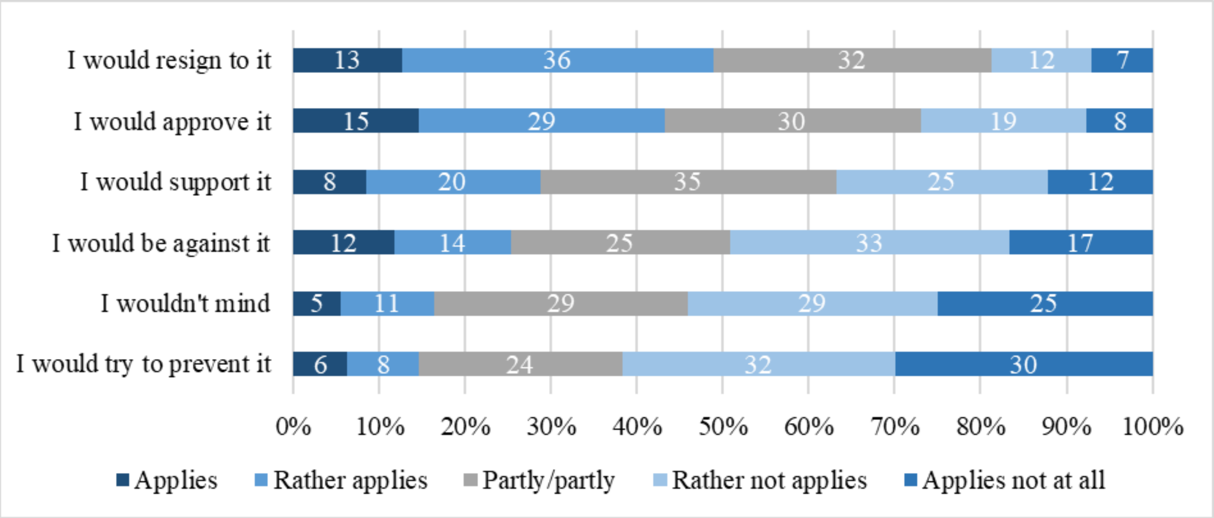


Figure 5.18: Option 3: Acceptance of hydrogen pipeline ("Imagine for now, a pipeline is to be built near your home for the transport of H_2. Would you accept the building project?"; n=512).

The number of people that would try to prevent the pipeline construction varies from 11 percent in Option 2 to 19 percent in Option 1. This indicates a moderately high percentage of active rejection of pipeline constructions. Retrofitting a pipeline, as in Option 2, is perceived somewhat more positively than building a new pipeline as in Option 1 and Option 3. However, the difference is rather small.

The most frequently selected condition under which the respondents would rather accept the pipeline constructions in their neighbourhood is with clearance the protection from health risks. Preservation of life quality, sufficient information, the liability of the operators and if it is the only possibility to realise the project are further relevant conditions. Compared to these conditions, aspects of participation are secondary to increase acceptance (see Figure 5.19).

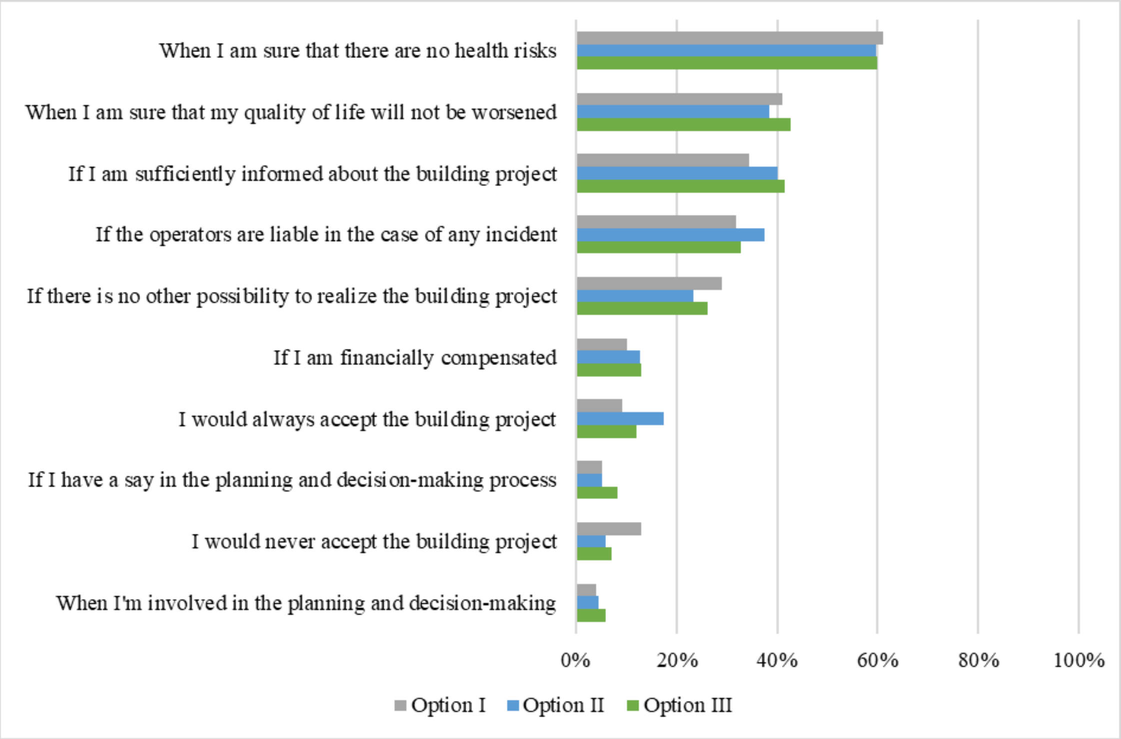


Figure 5.19: Conditions to increase acceptance ("When would you rather accept the building project? Please select a maximum of three answers."; n=1438)

Not-In-My-Back-Yard' (NIMBY)

Dear (1992) defines the term Not-in-my-backyard (NIMBY) as "[…] the motivation of residents who want to protect their turf. More formally, NIMBY refers to the protectionist attitudes of and oppositional tactics adopted by community groups facing an unwelcome development in their neighbourhood." [DEA92] It is applied to describe the phenomenon that people have a rather positive perception of a new development in general (such as new technologies), but not in their close neighbourhood. NIMBY often appears with energy technologies, where people approve the technology, but not the related (large-scale) infrastructure close to their home [DEV17].

To analyse the correlation of technology acceptance and acceptance of pipeline construction in the own neighbourhood, five types of acceptance were built: Supporters evaluate the technology as well as the pipeline construction in the own neighbourhood positively. Opponents evaluate the technology as well as the pipeline construction in the own neighbourhood negatively. Indifferent/ambivalent respondents are indifferent to both. NIMBYs have a supposedly contradictory attitude because they have a positive attitude towards the technology but a negative attitude towards the associated infrastructure in their own neighbourhood.

Regarding the three pipeline options – new CO_2 pipeline, new H_2 pipeline or a retrofitted H_2/natural gas pipeline – respondents show similar tendencies, but different intensities (see Table 5.10). Each option shows about one fifth of NIMBYs. Supporters are 30 to 40 percent per option and thus, significantly higher. Most supporters are in Option 2. By contrast, the number of opponents is much lower. However, it can be seen that the number of opponents in Option 1 is significantly higher than in Option 2 and 3. A large fraction is made up of indifferent/ambivalent who chose the 'partly/partly'-category when evaluating the pipeline construction.

The percentage of NIMBYs is only marginally lower for using existing infrastructure than building new infrastructure. This result leads to the assumption that people who are against an infrastructural intervention in their own neighbourhood do not distinguish between a new construction or a retrofit.

*Table 5.10: Types of Acceptance (technology acceptance*acceptance of pipeline infrastructure; n1=458; n2=468;n3=512).*

	Option 1	**Option 2**	**Option 3**
Type of acceptance	***Build new pipeline to transport CO2***	***Retrofit pipeline to transport H2/natural gas mix***	***Build new pipeline to transport H2***
	%	*%*	*%*
NIMBY	19.1 %	18.8 %	22.5 %
Supporters	35.8 %	42.1 %	32.6 %
Opponents	8.3 %	2.6 %	2.9 %
Indifferent/ Ambivalent	34.4 %	35.5 %	40.4 %
Others	1.7 %	1.1 %	1.4 %

It can therefore be seen that even in the very hypothetical case of this survey, NIMBY effects are observable, which initially seem to be contradictory attitudes. However, assuming that NIMBYs follow egoistic and irrational motives misses the actual issue and higher complexity of the seemingly contradictory attitudes. Especially place-based factors, such as peoples experience and place attachment as well as project-related factors, such as trust in stakeholders and being involved in the planning procedure, are explaining variables [DEV17]. Considering these aspects leads to a higher probability that NIMBY effects can be compensated.[9]

5.5.4 Acceptance of Procedures and Stakeholders

The third level of acceptance concerns the acceptance of procedures and stakeholders during implementation processes. The perceived fairness of large-scale projects was shown to be influenced by possibilities to participate and to be involved in the project planning phase [e.g. SCH16b; SCH16c; LAN17]. Transparent provision of information and the perceived level of one's own impact, which refers to the possibility that stated opinions are taken into account, were found to be central factors for successful participation processes [LAN17]. Asking for the willingness to participate in the planning of such a large-scale project, the majority of the respondents give positive answers (see Figure 5.20). Only 13 percent state not to be willing to participate. Of course, the percentage of people who express their willingness in a questionnaire is significantly higher than in a real case. However, the results reveal a theoretically high interest in participation procedures which underlines the importance of taking participation into account.

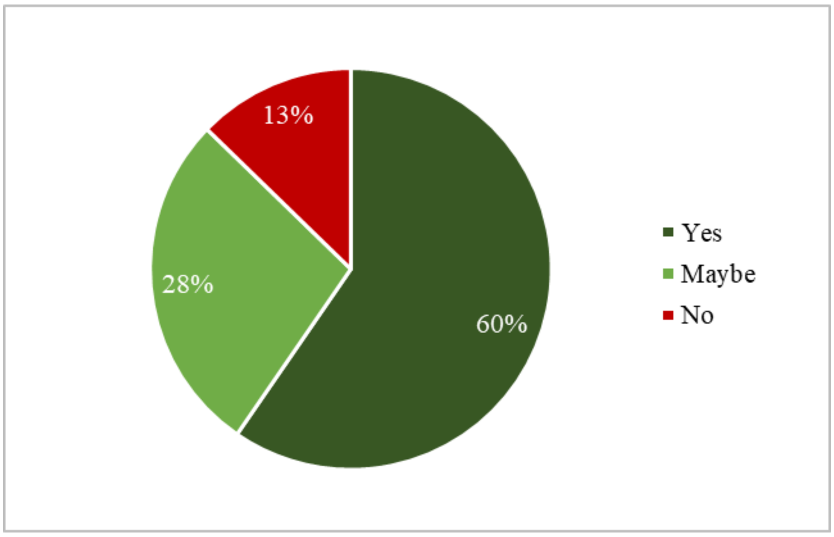


Figure 5.20: Participation in planning process ("Citizen participation procedures are procedures in which citizens are involved in the planning of major projects. Let us assume that in the course of a pipeline construction near your home, such a public participation procedure is planned: Could you imagine to participate?"; n=1438).

Trust in stakeholders who are involved in implementation processes is another crucial factor for social acceptance. Stakeholders like companies, industry associations, environmental associations or consumer advisors make themselves heard in order to assert and establish their views and interpretations. Stakeholders who are trusted are more likely to be heard by the public and more likely to shape and determine the public debate [Renn97; LÜT12]. Furthermore, a high level of trust in stakeholders who are involved in implementing projects has a positive influence on the attitude towards the technology as well as on the intention to act in a supportive way and vice

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[9] A detailed elaboration of the NIMBY effects in the German case study will be presented and published in "Glanz/Schönauer 2020: Hydrogen in Future Energy Systems: Social Acceptance of Technology and Large-Scale Infrastructure" at the conference Sustainable Development of Energy, Water and Environmental Systems (SDEWES) 2020, 1-5 September, Cologne.

versa [HUI14]. The central role of stakeholders in the implementation process was also shown in the macroeconomic scenario analysis (see section 3.2.1).

The respondents' trust varies strongly between the different stakeholder groups (see Figure 5.21). Civic stakeholders – environmental NGOs, consumer associations and citizens' initiatives – as well as stakeholders from science have the highest level of trust. However, trust towards citizens' initiatives is more ambivalent comparable to the other civic stakeholders. Political stakeholders from the EU, the federal and local government are met with a considerably lower level of trust. Large energy companies are the least trusted ones among the present stakeholders. This result confirms the findings of the stakeholder interviews (see section 5.4).

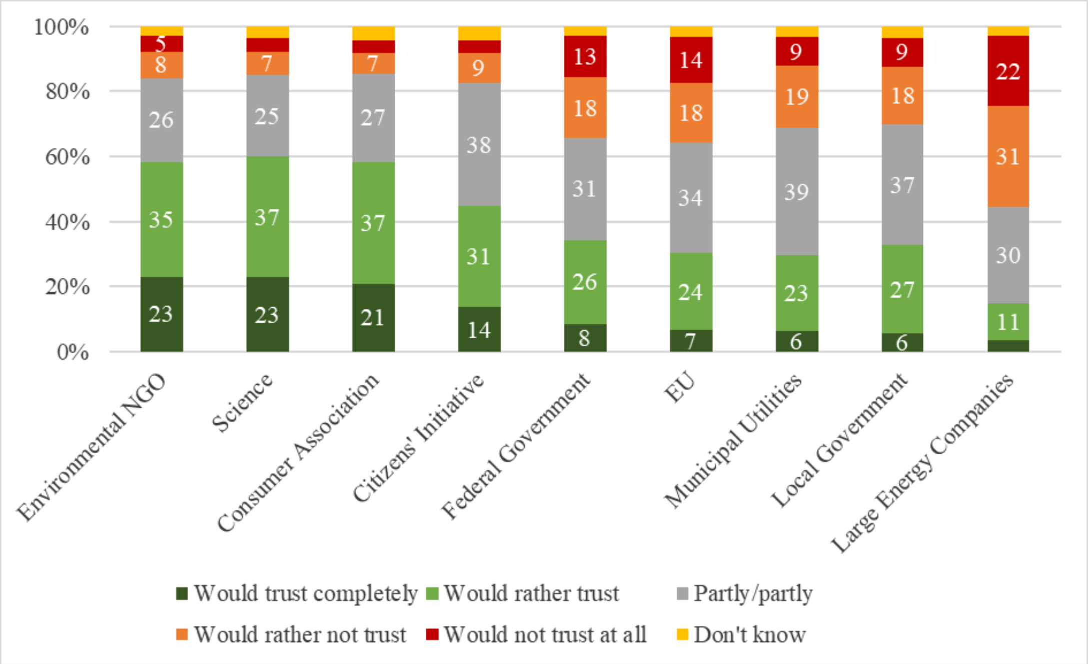

Figure 5.21: Trust in stakeholders ("How much would you trust information you receive from the following organisations?"; n=1438).

The knowledge that participation can contribute to increased acceptance and reduction of NIMBY effects (see section 5.5.3) and the respondents' interest in participation, illustrates the relevance of considering participation in implementation processes. Trust and acceptance can be increased through the involvement of civic stakeholders.

5.5.5 Who Accepts and Who Does not?

Next to aspects that are related to the technology or its implementation, acceptance is influenced by factors that are not directly linked to the object of acceptance. In this way, socio-structural characteristics as well as attitudes on environment and climate directly or indirectly influence the perception and acceptance of energy technologies [SCH17a].

5.5.5.1 Socio-structural Characteristics

The respondents were quoted by gender, age, education and the federal state (see Figure 5.22). Therefore, the socio-structural characteristics gender, age and education are nearly equivalent to the distribution of persons living in Germany. The net household income is underestimated in the survey as the average is higher in Germany.

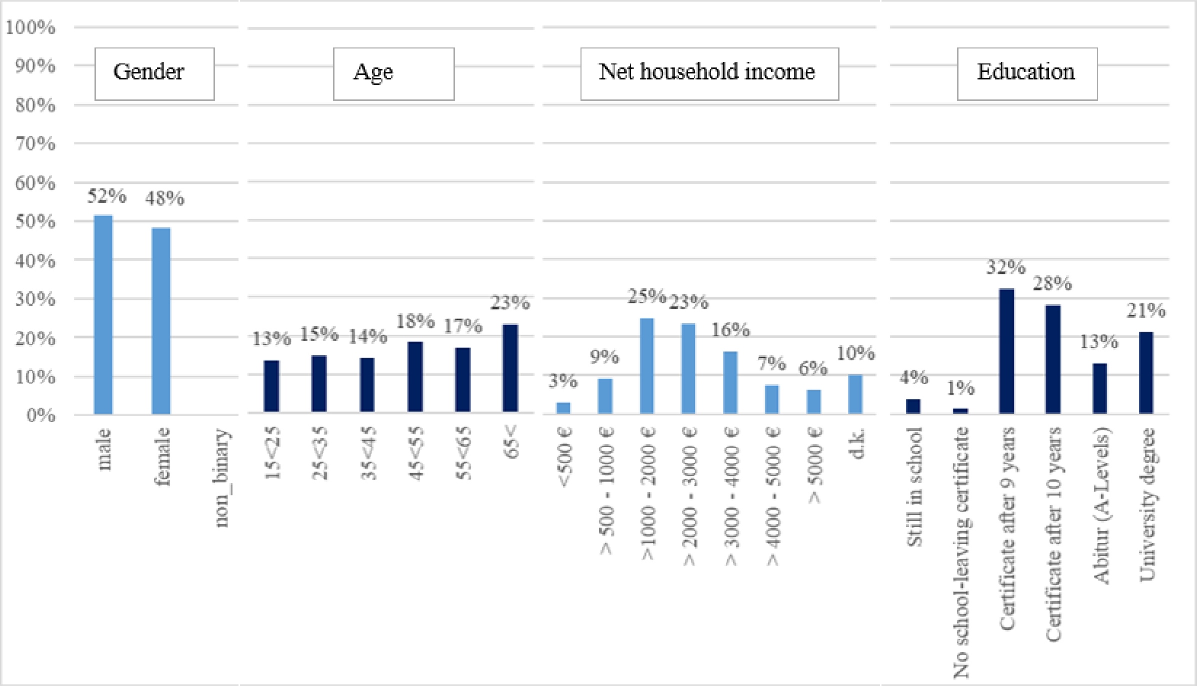

Figure 5.22: Socio-demographic characteristics (n=1438).

Age and education do not reveal correlations with the evaluation of the option. But gender and net household income show a weak correlation: women and households with higher income are more likely to positively evaluate the option.

Similar effects can be observed for the evaluation of the technology. Age and education do not reveal linear correlations with the assessment of CCS technologies. Gender correlates with the assessment: women tend to be more ambivalent, while more men evaluate CCS positive or negative. A linear correlation can be seen between income and the assessment of CCS: the higher the income, the more likely CCS is to be assessed positively.

The assessment of hydrogen technologies correlates with gender and education: women evaluate the technology ambivalent to positive, while the majority of men assess hydrogen positively. Regarding education, respondents with higher education (Abitur and unversity degree) as well as pupils evaluate hydrogen more positive than respondents with low to medium education (ceritifcate after nine and ten years). Income and age are not correlating with the assessment of hydrogen technologies.

Furthermore, life satisfaction was found to be a relevant factor for attitudes related to technology. A higher level of life satisfaction leads to more positive attitudes, while a lower level of life satisfaction leads to more negative attitudes [SCH17a].

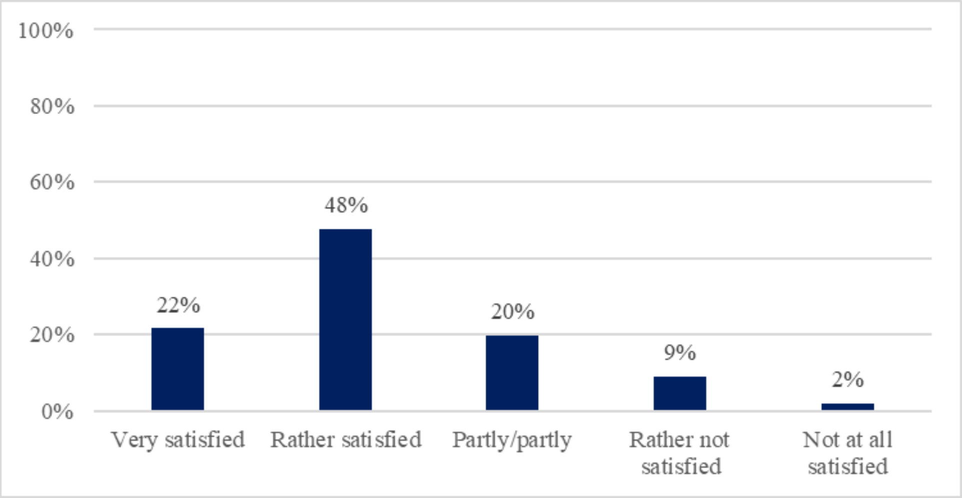

Figure 5.23: Life satisfaction ("How satisfied are you currently with your life in general?"; n=1438).

Most respondents express a high life satisfaction, only 11 percent of the respondents are rather not or not at all satisfied (see Figure 5.23). However, the evaluation of the options as well as the assessment of hydrogen as an energy carrier and CCS technologies show a weak, positive correlation with life satisfaction: The higher the life satisfaction, the more positive is the evaluation of the options and the assessment of the technologies.

5.5.5.2 Environmental and Climate Attitudes

At the time of the survey, the subject of climate change was very prominent in the media, especially through the protests 'Fridays for Future' and protests around the topic of phasing-out lignite in Germany. Therefore, it is not surprising that environment is the topic with the highest rating, when asking the respondents for the most important political topic in their opinion: half of the respondents evaluate environment as a priority topic, around a quarter of the respondents even as the first priority topic. In contrast, energy is a priority topic for only around 20 percent of the respondents (see Figure 5.24).

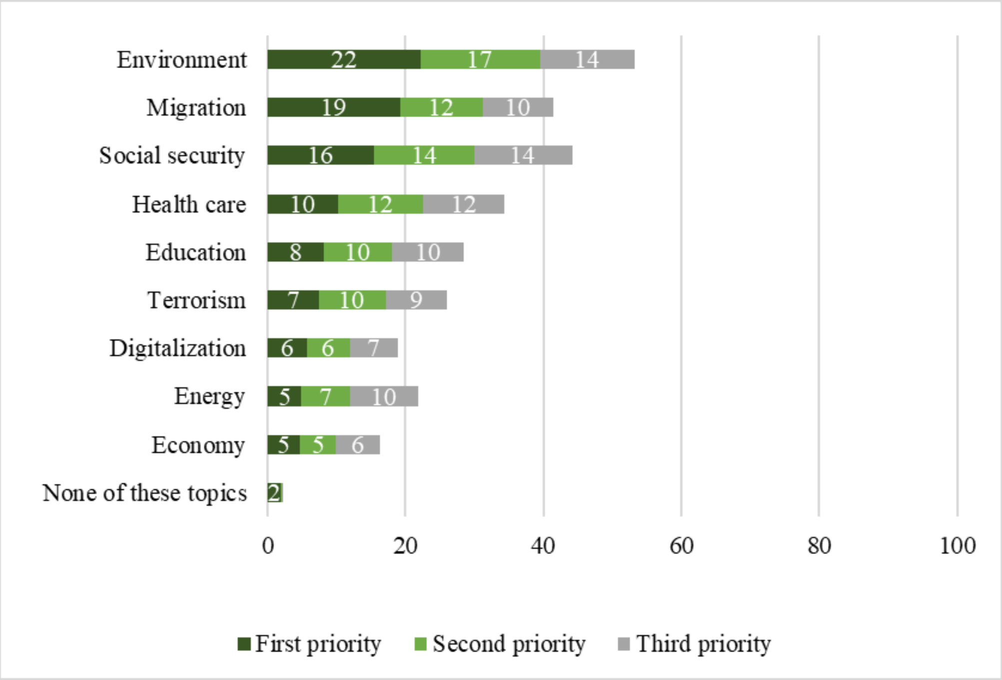

Figure 5.24: Priority of political topics ("Which of these topics are currently the most important for Germany in your opinion? Please choose the three most important topics; n=1438).

Having a more detailed look on the environmental issues, it becomes apparent that global warming/climate change is perceived as the most urgent topic next to plastic waste/microplastics (see Figure 5.25). Again, this rating has to be looked at against the background of intensive reporting on climate change at the time of the survey.

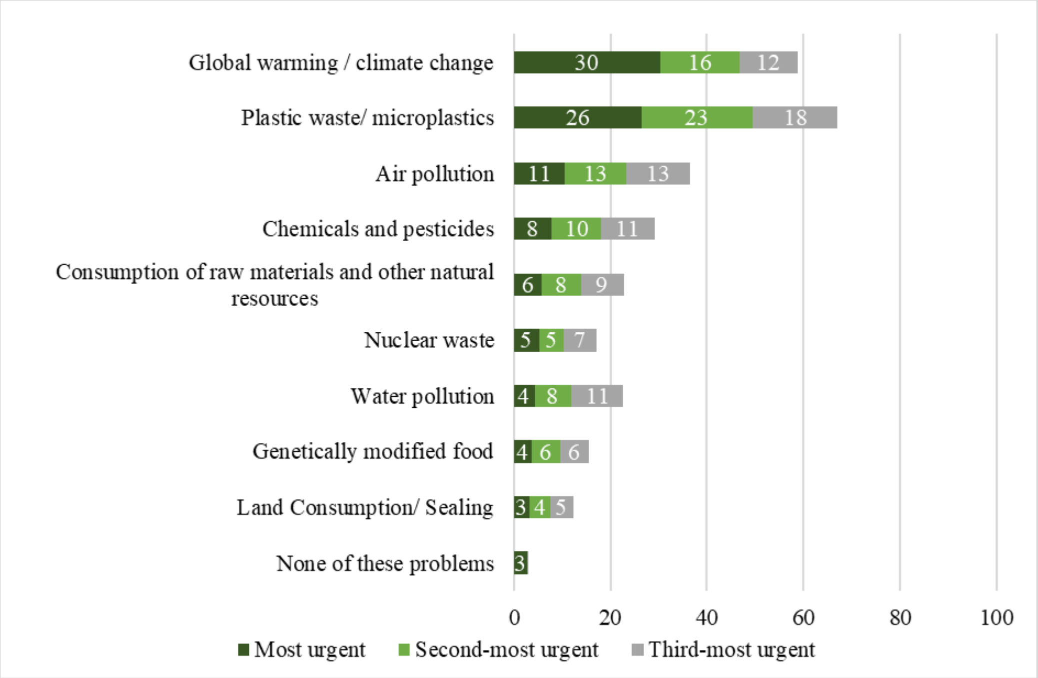

Figure 5.25: Perception of environmental problems ("Here is a list of various environmental problems. In your opinion, which of these problems are currently most urgent for Germany? Please choose three problems"; n=1438).

These results indicate a high level of problem perception regarding environmental issues and especially climate issues among the respondents, while energy itself tends to be given less priority as a political issue. Thus, climate change issues are more related to environmental policy than to energy policy.

The problem perception is also reflected in the respondents' concerns about environment and climate change. About 40 percent each are very concerned about environment and climate change. Only a very small number of respondents state that they are rather not or not concerned at all (see Figure 5.26).

Environmental concerns (n=1433)   Concerns on climate change (n=1436)

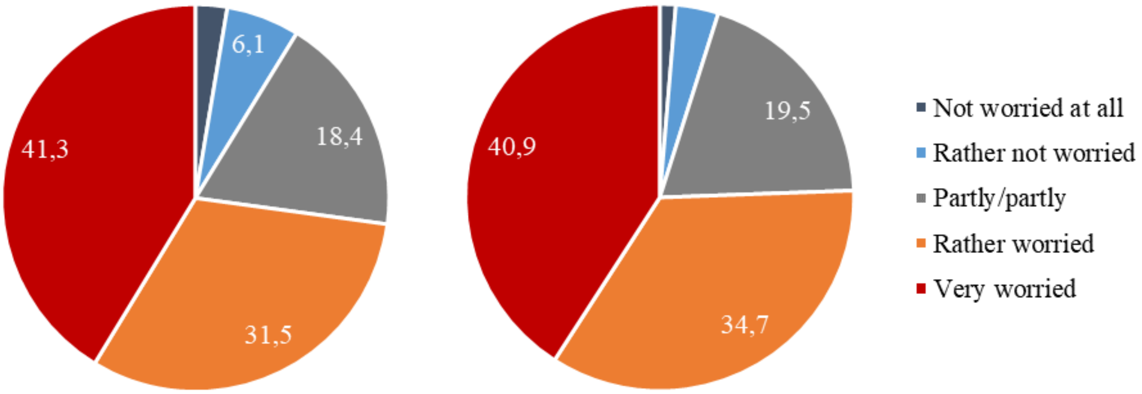

Figure 5.26: Environmental concerns and concerns on climate change ("How concerned are you about environmental issues?"/ "How concerned are you about climate change?").

Activism in environmental issues – measured by membership in an environmental organisation – is with 3.5 percent on about the same low level as in the German population (2.7 % in Allbus 2014) [GES18]. However, more than 40 percent can imagine to join an environmental organisation.

Also, the majority of respondents is aware of human contribution to climate change and is thinking that climate change is caused mainly due to human action (see Figure 5.27). Correspondingly, more than 60 percent of the respondents feel very or rather personally responsible for climate change, around a quarter feel partly responsible and only 10 percent feel rather not or not at all responsible.

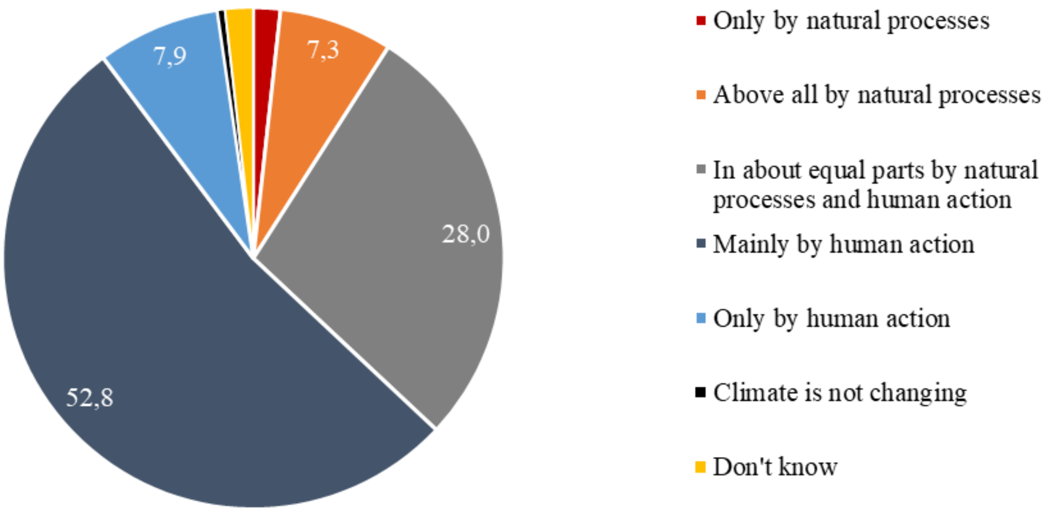

Figure 5.27: Cause of climate change ("Do you think that climate change is caused by natural processes, by human activity or by both?"; n=1438).

Also, the political concept for fighting climate change - the German energy transition – is met with broad acceptance. More than 60 percent are totally or rather for the energy transition, 28 percent are partly for the energy transition. Only around 10 percent are rather or totally against the transition.

A basic assumption for accepting 'new' and climate-friendly energy technologies is that human-made climate change is acknowledged. However, the results do not reveal a correlation between the acknowledgment of human made climate change and the assessment of H_2 and CCS technologies. This may be because around 90 percent of the respondents think that climate change is at least partly caused by human activity which leads to a small variance (see Figure 5.27).

The correlation between the acceptance of the energy transition and the evaluation of H2-CCS chains is assumed to be more complex. As hydrogen technologies are in line with the main program of the energy transition – the expansion of renewable energies – it is expected that accepting the German energy transition is positively influencing the acceptance of hydrogen technologies. In contrast, CCS technologies are expected to not be associated with the main goals of the German energy transition at first sight. Therefore, no influence from the acceptance of the energy transition on the acceptance of CCS technologies is expected. Indeed, the findings indicate that a positive correlation exists between the assessment of the German energy transition and the assessment of hydrogen technologies, while there is no correlation between the assessment of the energy transition and the assessment of CCS technologies. Furthermore, the findings reveal that a positive assessment of the energy transition comes along with a positive assessment of the options and vice versa.

Finally, self-efficacy of the respondents was measured by assessing the own potential to influence climate change through personal behaviour. On a scale from one to ten, the majority of respondents locate themselves from five to eight, which indicates a rather high level of perceived self-efficacy (see Figure 5.28).

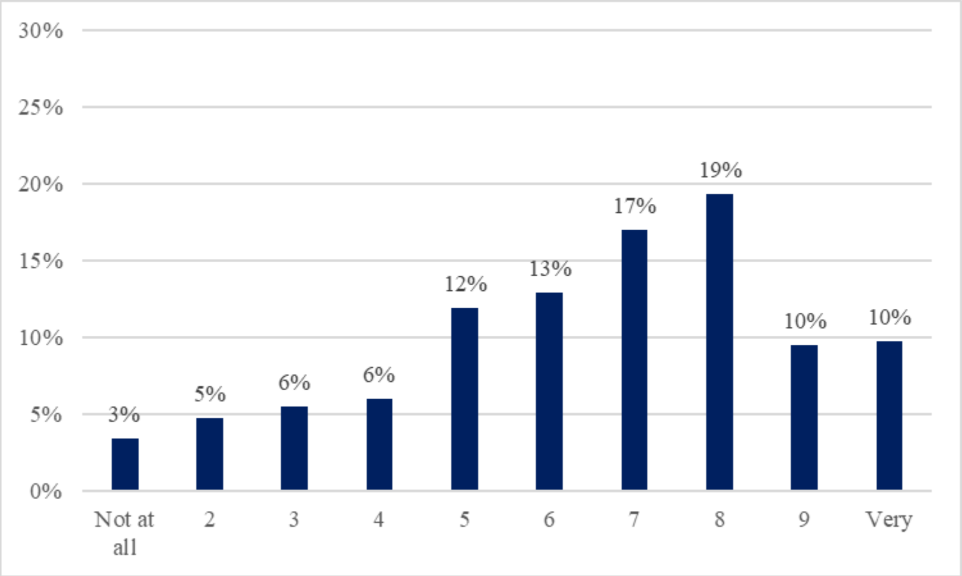

Figure 5.28: Personal impact on climate change ("In your opinion, how likely is it that your personal behaviour will help to counteract the effects of climate change?"; n=1438).

Climate and environmental attitudes also show correlations with the evaluation of the options. The higher the concern for the environment and/or climate, the higher the assessment of self-efficacy and the more positively the energy transition is assessed, the more positively the options are assessed.

5.5.5.3 Social Milieu

On the basis of the socio-structural variables and variables on attitudes to climate change, similar structures in the data were examined applying a hierarchical cluster analysis. This method is used to identify respondents that are similar in terms of socio-structural characteristics, attitudes towards climate change issues and satisfaction and combine them in groups. Four types were identified, named after the attribute that distinguishes them most from the other types: the environmental ideologist, the climate change indifferent, the unsatisfied and the achiever.

Table 5.11: Types by social milieu

	Environmental Ideologist	**Climate Change Indifferent**	**Unsatisfied**	**Achiever**
Socioeconomic				
Education	low	low to medium	medium to high	high
income	low	low to medium	medium	high
Attitudes to climate change				
Concerns	high	medium	high	high
Attitude energy transition	high	ambivalent	high	high
Self-efficacy	high	low	medium	high
Satisfaction with life	high	Medium to high	low	high

<u>Environmental Ideologist (n=401)</u>: This group is characterised by a low socioeconomic status but a high level of satisfaction and attaches great importance to the issue of climate change and energy transition. Among this type are around 40 percent retired persons as well as nearly all pupils in the survey (n=21). Accordingly, around half of the respondents in this group are before or after their work life, which may partly explain the low socio-economic status. The environmental

ideologists are voters of the Christian democrats (23%), the Green party (17%) and the Social democrats (16 %).

Climate Change Indifferent (n=168): The group of climate change indifferent have a low to medium socioeconomic status and are characterised above all by their more ambivalent attitude towards the issues of climate change and energy transition compared to the other groups. 36 percent of the climate change indifferent are retired persons, while less young persons belong to this type. 70 percent are male respondents. Furthermore, this type has the highest number of AFD[10] voters (30 %).

Unsatisfied (n=277): The group of unsatisfied have a medium socioeconomic status and are characterised above all by their lower level of life satisfaction compared to the other groups. At 10 percent, the unsatisfied have the largest number of unemployed respondents. Besides, 40 percent of this type live in a single-household. The highest number votes the left party (18%) as well as the AFD (17 %).

Achiever (n=369): The group of achievers differentiates itself from the other groups through its comparatively high socioeconomic status. The achievers are the group with the highest number of young people. More than half of the respondents are full-time employees. Around a quarter votes for each the Green party and the Christian democrats.

Analysing the overall evaluation of the options considering the four identified types confirms a rather positive overall assessment among all types, but at the same time significant differences (see Figure 5.29). Over 60 percent of the environmental ideologists and the achievers state a positive evaluation. 20 percent of the environmental ideologist even state a very positive evaluation. A less positive evaluation state the climate change indifferent with 40 percent of positive and 23 percent of negative voices. 50 percent of the unsatisfied state a positive and 21 percent a negative evaluation.

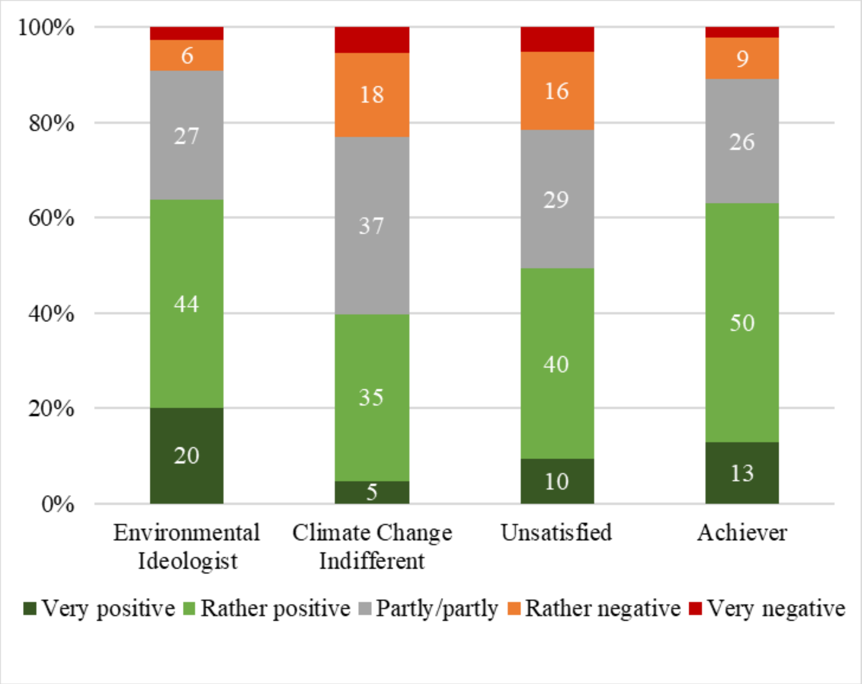

*Figure 5.29: Social milieu*evaluation of options (n=1215).*

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[10] Alternative für Deutschland (AFD) is a right-wing and climate sceptical party that has been in the German parliament since 2017.

Similar tendencies are observable when analysing the evaluation of hydrogen and CCS technologies considering the four types. The achievers evaluate CCS and H_2 technologies the most positive, innovative and safe. The environmental ideologist is very close to the achiever in their evaluation. In contrast, the climate change indifferent and the unsatisfied are close together in their evaluation and evaluate the technologies less positive, less innovative and less safe.

This typology provides a more detailed insight into the interplay of socio-economic variables, attitudes towards climate change and satisfaction regarding acceptance of the options. The social groups created by a cluster analysis present a more accurate explanation for the acceptance of the options and technologies than the variables themselves. Social groups which are characterised by a great importance to the issue of climate change and high satisfaction evaluate the options and technologies more positive, independent of the socio-economic status. In contrast, groups that are characterised with a lower socio-economic status and less importance of climate change issues or a lower level of satisfaction, tend to evaluate the options and technology less positive.

5.6 Summary and Conclusion

Most of the respondents gave a positive assessment of Options 2 and 3, while Option 1 is viewed positively by around 40 percent. In all three options, about one third of the respondents assesses the option ambivalent. Within the H_2-CCS chains, aspects of hydrogen technology and related infrastructure are rated more positively than CCS technologies and related infrastructure. The greatest risks for the acceptance of the options are thus posed by CCS technology.

The aspect of CO_2 storage has the strongest effect on the overall assessment of the options, although in none of the options CO_2 storage is planned in Germany. The more negative storage is perceived, the more negative the option is assessed. The perception of storage is thus of greater relevance than the perception of CO_2 capture and transport. The findings show that storage in the Netherlands is rated negatively by 32 percent, while storage in Norway it is rated negatively by only 20 percent. From these findings the thesis can be derived that the assessment of CO_2 storage turns out more positive with increasing distance of the storage location from Germany. A further explanatory approach is that the hydrogen framing of Option 2 and Option 3 has a positive influence on the assessment of CO_2 storage in Norway.

Hydrogen as an energy carrier offers a high chance for the acceptance of these options. However, there are risks for acceptance when it comes to infrastructural consequences, such as the construction of pipelines to transport hydrogen. Therefore, the lower the infrastructural consequences, the higher the expected acceptance. As far as infrastructure is concerned, the transport of hydrogen or a hydrogen-natural gas mixture is perceived much more positively than the transport of CO_2. The acceptance of the construction of a new pipeline system depends strongly on the acceptance of the corresponding technology: If the technology is perceived positively, the associated pipeline is also perceived more positively.

Hydrogen as an energy carrier is perceived as positive and innovative by the majority of those surveyed. Only when weighing up safety and risk is the perception of the respondents rather ambivalent. CCS technologies on the other hand, are predominantly rated ambivalent on the positive-negative scale and the safety-risk scale. Only the innovation level of CCS technologies is rated as high as for hydrogen by the respondents.

However, the results reveal that there is little knowledge about the technologies. 30 percent of the respondents had never heard of hydrogen technologies before the survey and only just under ten percent said they knew a lot about the technologies. As many as 55 percent of those surveyed had never heard of CCS technologies and only four percent of those surveyed said they knew a lot about them. A knowledge-based assessment of the options was realised by an information-based questionnaire design. Regarding hydrogen technology, slightly more positive assessments are observable with increasing knowledge. Regarding CCS technology more knowledge does not linearly lead to more positive perceptions, but to a stronger polarisation in positive as well as negative assessments.

Lack of acceptance of new infrastructure is often referred to the not-in-my-backyard effect (NIMBY). NIMBY occurs when a technology is generally perceived positively, but the associated infrastructure is not accepted in the own neighbourhood. The comparison of the general perception of the technology with the acceptance of a corresponding pipeline in one's own neighbourhood shows that NIMBY effects can also be found in the results of the German case study. Approximately 15 to 20 percent of the respondents show NIMBY effects when assessing the construction of a new pipeline. In our analyses, however, we have also found that the NIMBY effects do not necessarily mean that pipeline construction is rejected under any circumstances, but that there are certain factors that increase acceptance. In order to increase acceptance of new infrastructure, trust in the stakeholders involved in implementation processes, procedural transparency and opportunities for public participation have proven to be important instruments. However, most important for accepting new infrastructure are safety from health risks and the preservation of the life quality.

The analyses have also shown that socio-structural variables, attitudes towards climate change and satisfaction with life have an influence on technology acceptance and the evaluation of the options. Using a cluster analysis, four groups have emerged from combining these variables. The group of climate change indifferent evaluates the options more negative. Besides, the group of respondents with a low socio-economic status and low life satisfaction states a more sceptical assessment. In contrast, the group of environmental ideologists and the achievers regarding socio-economic variables assess the options more positively.

In order to categorise the results from the online survey, they are fed back with the results from the stakeholder interviews. The stakeholder interviews revealed a high openness to new technologies and the acknowledgment of the potential of CCS to reduce CO_2 emissions, but only in fields of application where no postponement or delay of phasing-out fossil energies is perceived. Therefore, the consensus to CCS is limited to decarbonise industry-induced emissions and bioenergy (BECCS). Hydrogen is generally perceived positively, especially because of its connectivity to fossil as well as to renewable energy systems.

The rather positive perception of the three options with a large proportion of ambivalent respondents suggests that there is a high potential for acceptance, although the acceptance depends on the actual implementation process. Hydrogen technologies in the options meet with high acceptance in particular, because of both: their perception as an innovative technology and because they can be connected to renewable energy systems. Under certain aspects, however, the acceptance of CCS is also higher, for example to decarbonise industry and bioenergy (BECCS) or for the production of hydrogen (Option 2 and Option 3). In the case of large-scale infrastructure projects involving both CCS and hydrogen technologies, the early involvement of local residents in the planning processes must be taken into account in order to achieve acceptance.

5.7 References

[ACH10] ACHTERBERG, P.; HOUTMAN, D.; VAN BOHEMEN, S. ET AL.: *Unknowing but supportive? Predispositions, knowledge, and support for hydrogen technology in the Netherlands*. In: *International Journal of Hydrogen Energy* 35 (12), pp. 6075–6083. 2010.

[ARN19] ARNING, K.; OFFERMANN-VAN HEEK, J.; LINZENICH, A. ET AL.: *Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany*. In: *Energy Policy* 125, pp. 235–249. 2019.

[BES09] BEST-WALDHOBER, M. de; DAAMEN, D.; FAAIJ, A. ET AL.: *Informed and uninformed public opinions on CO2 capture and storage technologies in the Netherlands*. In: *International Journal of Greenhouse Gas Control* 3 (3), pp. 322–332. 2009. doi.org/10.1016/j.ijggc.2008.09.001

[BRA18] BRAUN, C.; MERK, C.; PÖNITZSCH, G. ET AL.: *Public perception of climate engineering and carbon capture and storage in Germany: survey evidence*. In: *Climate Policy* 18 (4), pp. 471–484. 2018.

[BRU13] BRUNSTING, S.; BEST-WALDHOBER, M. de; TERWEL, B. W. ET AL.: *'I Reject your Reality and Substitute my Own!' Why More Knowledge about CO2 Storage Hardly Improves Public Attitudes.* In: *Energy Procedia* 37, pp. 7419-7427. 2013.

[BUS19] BUSCHMANN, P.; OELS, A.: *The overlooked role of discourse in breaking carbon lock-in: The case of the German energy transition*. In: *WIREs Clim Change* 10 (3), e574. 2019.

[DEA92] DEAR, M.: *Understanding and Overcoming the NIMBY Syndrome*. In: *Journal of the American Planning Association* 58 (3), pp. 288–300. 1992.

[DEV17] DEVINE-WRIGHT, P.; BATEL, S.: *My neighbourhood, my country or my planet? The influence of multiple place attachments and climate change concern on social acceptance of energy infrastructure*. In: *Global Environmental Change* 47, pp. 110–120. 2017.

[DÜT15] DÜTSCHKE, E.; SCHUMANN, D.; PIETZNER, K. ET AL.: *Chances for and Limitations of Acceptance for CCS in Germany*. In: Axel Liebscher und Ute Münch (Hg.): Geological storage of CO2 - long term security, Bd. 4. Cham [Germany]: Springer, pp. 229–245. 2015. ISBN: 978-3-319-13929-6.

[DÜT16] DÜTSCHKE, E.; WOHLFARTH, K.; HÖLLER, S. ET AL.: *Differences in the public perception of CCS in Germany depending on CO2 source, transport option and storage location*. In: *International Journal of Greenhouse Gas Control* 53 (Supplement C), pp. 149–159. 2016.

[FLA19] FLAMME, S.; BENRATH, D.; GLANZ, S. ET AL.: *ELEGANCY: The Interdisciplinary Approach of the German Case Study to Enable a Low Carbon Economy by Hydrogen and CCS. In: Energy Procedia* 158, pp. 3709–3714 2019.

[FIS08] FISCHEDICK, M.; CREMER, C.: *Sozioökonomische Begleitforschung zur gesellschaftlichen Akzeptanz von Carbon Capture and Storage (CCS) auf nationaler und internationaler Ebene. Gemeinschaftsprojekt des Wuppertal Instituts, des Forschungszentrum Jülich (STE), dem Fraunhofer Institut (ISI) und der BSR Sustainability GmbH ; Endbericht*. Wuppertal, Hannover: Technische Informationsbibliothek u. Universitätsbibliothek. 2008.

[FIS09] FISCHEDICK, M.; PIETZNER, K.; SUPERSBERGER, N. ET AL.: *Stakeholder acceptance of carbon capture and storage in Germany*. In: *Energy Procedia* 1 (1), pp. 4783–4787. 2009.

[GAL18] GALVIN, R.: *Trouble at the end of the line: Local activism and social acceptance in low-carbon electricity transmission in Lower Franconia, Germany*. In: *Energy Research & Social Science* 38, pp. 114–126. 2018.

[GES18] GESIS-LEIBNIZ-INSTITUT FÜR SOZIALWISSENSCHAFTEN: *Allgemeine Bevölkerungsumfrage der Sozialwissenschaften ALLBUS 2014*. Unter Mitarbeit von Andreas Diekmann, Detlef Fetchenhauer, Frauke Kreuter, Karin Kurz, Stefan Liebig, Michael Wagner et al. 2018.

[GLA20] Glanz, S.; Schönauer, A.-L.: *Towards a Low-Carbon Society via Hydrogen and Carbon Capture and Storage: Social Acceptance from a Stakeholder Perspective.* In: *Sustainable Development of Energy, Water and Environment Systems* forthcoming.

[HAM13] Hammersley, M.: *What is Qualitative Research?*: Bloomsbury Academic. 2013. - ISBN: 978-1-7809-3335-1.

[HEI08] Heinz, B.; Erdmann, G.: *Dynamic effects on the acceptance of hydrogen technologies—an international comparison*. In: *International Journal of Hydrogen Energy* 33 (12), pp. 3004–3008. 2008.

[HIL18] Hildebrand, J.; Rau, I.; Schweizer-Ries, P.: *Akzeptanz und Beteiligung – ein ungleiches Paar*. In: Lars Holstenkamp und Jörg Radtke (eds.): Handbuch Energiewende und Partizipation. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 193–209. 2018.

[HOP95] Hopf, C.; Rieker, P.; Sanden-Marcus, M. et al.: *Familie und Rechtsextremismus. Familiale Sozialisation und rechtsextreme Orientierungen junger Männer*. Weinheim: Juventa Verlag. 1995.

[HUI07] Huijts, N. M.A.; Midden, C. J.H.; Meijnders, A. L. et al.: *Social acceptance of carbon dioxide storage*. In: *Energy Policy* 35 (5), pp. 2780–2789. 2007.

[HUI12] Huijts, N.; Molin, E.; Steg, L.: *Psychological factors influencing sustainable energy technology acceptance. A review-based comprehensive framework*. In: *Renewable and Sustainable Energy Reviews* 16, pp. 525–531. 2012.

[HUI14] Huijts, N.M.A.; Molin, E.J.E.; van Wee, B. et al.: *Hydrogen fuel station acceptance. A structural equation model based on the technology acceptance framework*. In: *Journal of Environmental Psychology* 38, pp. 153–166. 2014.

[HUI15] Huijts, N.M.A.; van Wee, B.: *The evaluation of hydrogen fuel stations by citizens. The interrelated effects of socio-demographic, spatial and psychological variables*. In: *International Journal of Hydrogen Energy* 40 (33), pp. 10367–10381. 2015.

[HYA17] FCH-JU-2013-1 (Hrsg.): *Projekt HYACINTH. Ergebnisse zur Akzeptanz der Bevölkerung*. 2017.

[LAN17] Langer, K.; Decker, T.; Menrad, K. et al.: *Public participation in wind energy projects located in Germany: Which form of participation is the key to acceptance?* In: *Renewable Energy* 112, pp. 63–73. 2017.

[LEI17] Leipprand, A.: *From conflict to consensus?* Shaker Verlag GmbH. Dissertation. 2017.

[LÜT12] Lüthje, C.; Neverla, I.: *Wissen, Diskurse, Erzählungen im Kontext von Mediatisierung. Konzeptionelle Überlegungen zur sozialen Konstruktion von Klimawandel*. In: Das Medien-Klima : Fragen und Befunde der kommunikationswissenschaftlichen Klimaforschung. Wiesbaden: Springer VS, pp. 143–169. 2012. ISBN: 978-3-531-17752-6.

[PIE11] Pietzner, K.; Schumann, D.; Tvedt, S. D. et al.: *Public awareness and perceptions of carbon dioxide capture and storage (CCS). Insights from surveys* *administered to representative samples in six European countries*. In: *Energy Procedia* 4, pp. 6300–6306. 2011.

[REN97] RENN, O.; ZWICK, M. M.: *Risiko- und Technikakzeptanz*. Berlin u.a.: Springer. 1997.

[REN16] RENN, O.; MARSHALL, J. P.: *Coal, nuclear and renewable energy policies in Germany: From the 1950s to the "Energiewende"*. In: *Energy Policy* 99, pp. 224-232. 2016.

[REU16] REUSSWIG, F.; BRAUN, F.; HEGER, I. ET AL.: *Against the wind: Local opposition to the German Energiewende*. In: *Utilities Policy* 41, pp. 214–227. 2016.

[SCH14] SCHUMANN, D.; DUETSCHKE, E.; PIETZNER, K. ET AL.: *Public Perception of CO2 Offshore Storage in Germany. Regional Differences and Determinants*. In: *Energy Procedia* 63, pp. 7096–7112. 2014.

[SCH16a] SCHMIDT, A.; DONSBACH, W.: *Acceptance factors of hydrogen and their use by relevant stakeholders and the media*. In: *International Journal of Hydrogen Energy* 41 (8), pp. 4509–4520. 2016.

[SCH16b] SCHROETER, R.; SCHEEL, O.; RENN, O. ET AL.: *Testing the value of public participation in Germany: Theory, operationalization and a case study on the evaluation of participation*. In: *Energy Research & Social Science* 13, pp. 116–125. 2016.

[SCH16c] SCHWEIZER, P.-J.; RENN, O.; KÖCK, W. ET AL.: *Public participation for infrastructure planning in the context of the German "Energiewende"*. In: *Utilities Policy* 43, pp. 206–209. 2016.

[SCH17a] SCHÖNAUER, A.-L.: *Industriefeindlichkeit in Deutschland. Eine empirische Analyse aus sozialwissenschaftlicher Perspektive*. Wiesbaden: Springer Fachmedien Wiesbaden. 2017.

[SCH17b] SCHUMANN, D.: *Public Perception of CO 2 Pipelines*. In: *Energy Procedia* 114, pp. 7356–7366. 2017.

[TER13] TER MORS, E.; TERWEL, B. W.; DAAMEN, D. D.L. ET AL.: *A comparison of techniques used to collect informed public opinions about CCS. Opinion quality after focus group discussions versus information-choice questionnaires*. In: *International Journal of Greenhouse Gas Control* 18, pp. 256–263. 2013.

[WAL11] WALLQUIST, L. I.: *Public perception of carbon dioxide capture and storage*. Zugl.: Zürich, Diss., Eidgenössische Technische Hochschule ETH Zürich, Nr. 19952, 2011. Zürich: ETH. 2011.

[ZAU18] ZAUNBRECHER, B. S.; KLUGE, J.; ZIEFLE, M. ET AL.: *Exploring Mental Models of Geothermal Energy among Laypeople in Germany as Hidden Drivers for Acceptance*. In: *J. sustain. dev. energy water environ. syst.* 6 (3), pp. 446–463. 2018.

[ZIM12] ZIMMER, R.; WELKE, J.: *Let's go green with hydrogen! The general public's perspective*. In: *International Journal of Hydrogen Energy* 37 (22), pp. 17502–17508. 2012.

[ZOE12] ZOELLNER, J.; SCHWEIZER-RIES, P.; RAU, I.: *Akzeptanz Erneuerbarer Energien*. In: Thorsten Müller (ed.): 20 Jahre Recht der Erneuerbaren Energien, 1st ed. (Online-ed.). Baden-Baden: Nomos Verlag, pp. 91–107. 2012.

6 CONCLUSIONS

The results of the German case study reveal that significant barriers impair all examined infrastructure options to integrate the German economy into H_2-CCS chains. This impairment is especially due to the unfavourable legal framework (see section 4), the lack of an H_2 and CO_2 transport market and missing business models. However, the respective markets and related business models can develop and the legal framework can be amended. **Until 2035 and under certain conditions, the examined infrastructure options can be realised.** The feasibility depends on how the future will look like: A high level of low-carbon transformation in general, commitments from political decision-makers, the economy and the society as well as a low level of conflict increase the feasibility (see section 3.2). Moreover, many societal stakeholders accept H_2-CCS options more readily in a context in which they accelerate the overall transition and avoid lock-in effects in respect of fossil energies (see section 5.4).

Based on the disciplinary analyses and their combination, the general base options can be refined to best case options. Furthermore, the feasibility of the options in respect of the necessary infrastructure and its requirements can be assessed. Thus, the so produced concepts can be evaluated in regard to their effect on the integration of the German economy in H_2-CCS chains to decarbonise it as well as to the connected costs and risks. Distinct differences between the three infrastructure options can be observed:

- The creation of a **dedicated H_2 transmission network** that is largely based on repurposed natural gas pipelines and prioritises green hydrogen is identified as the **most feasible infrastructure option** to integrate the German economy into H_2-CCS chains. The hurdles for this option are manageable and its requirements can most likely be met (see section 3.3). In this context, the general acceptance of H_2 technologies can be named as an exemplary fostering aspect (see section 5.5.2). Also, rather minor infrastructural changes are more easily accepted (see section 5.5.3). Moreover, in regard to the transport of H_2 and related CO_2 abatements, dedicated H_2 networks show comparative cost advantages over H_2 blending options (see section 2.6). Additionally, a dedicated H_2 transmission network is most suitable to ramp up an H_2 economy quickly and to integrate substantial amounts of blue hydrogen without a significant conflict with green hydrogen. Furthermore, the transition from H- to L-gas in the Netherlands and parts of Germany presents a unique opportunity for extensive repurposing. And in respect of future developments, a growing dedicated H_2 transmission network can flexibly react to market developments, new policies and technological advancement; it can even relatively easily replace the natural gas grid if necessary. But **actions to enable this option have to be taken quickly** (see section 4.3.5).
- The injection of substantially increased amounts of H_2 into the natural gas grid, for which a number of very different forms – with respective benefits and disadvantages – can be considered, is a similarly feasible option. Investments in pipeline retrofitting are cost-intensive but revealed to be realistic as investors are increasingly attracted by business opportunities related to H_2. And legal constraints can be removed although it requires challenging interventions, which are susceptible to intense conflicts (see section 4.2.5) However, this option only allows a limited integration into H_2-CCS chains since a priority of green hydrogen in a limited share of H_2 will leave little space for blue hydrogen. Whereas, eliminating the priority of green gas would reduce the clear connection of this option to renewable energies and could therefore undermine a basis of the broad acceptance of H_2 technologies (see section 5.4). Additionally, any further decarbonisation that is based on this option would demand another substantial increase of the H_2 share, which will again require significant efforts and provoke conflicts.

- While an extensive pipeline network for CO_2 is hardly achievable by 2035 (see section 4.1.4), a network that includes individual pipelines and shipping is feasible and can include most relevant point sources (see section 2.5). The additional costs of using ship transport are significant (see section 2.2.2.2) but appear to be manageable in the light of the non-financial costs of extensive new structures. However, there are indicators that ship transport – like extensive new infrastructure – might have problems with social acceptance as well (see section 5.5.1.1). Anyways, the main hurdles are whether there will be a political will to directly engage in CCS despite public scepticism (see section 5.6) and whether business models for CCS can develop.

The benefits and disadvantages of the three infrastructure options are closely connected to the general constellation in respect of established and new systems. For a CO_2 pipeline network, an extensive new infrastructure is needed, which is connected to substantial effort and investment costs and produces frictions with third parties and environmental costs. These grievances can be reduced by also making use of the established infrastructure for river shipping. The blending of substantial amounts of H_2 in the natural gas transmission network does not need significant new infrastructure. But it requires and it is accompanied by intensive interventions in the natural gas system; these interventions are complex, extensive and challenging, affect many stakeholders and produce manifold points of conflict. Dedicated H_2 transmission networks can use established assets to create a new infrastructure. Thus, the established natural gas system remains largely untouched while there is limited need for new intrusive constructions. This fact avoids or reduces conflicts and friction both within the natural gas system and in regard to investment and environmental costs. However, to allow an organic and yet appropriate growth of the backbone, timely action is required.

These observations can be generalised: Conflicts, barriers and costs can be reduced by using existing assets to create an alternative decarbonised system while avoiding intensive interventions in the established systems; to allow a gradual and organic replacement of the established system with little conflict, this approach demands prompt actions. This observation might be transferrable to other areas of climate action and transition.

Among the different infrastructure options, there is no significant conflict. Thus, they can be pursued simultaneously. In contrast, there is a positive interaction between dedicated H_2 transmission networks and the blending of H_2: An H_2 backbone makes H_2 – including blue hydrogen – easily available, which can help to stabilise a blended system, which requires a permanent inflow of H_2. Hence, the blending option can be seen as complementary to the creation of a dedicated H_2 system. By contrast, the transport of CO_2 can be regarded independently.

To decarbonise the German infrastructure through H_2-CCS chains, it is recommended to focus now on the creation of a dedicated H_2 transmission network and its connection to sources of blue hydrogen. This network is long-term designed for green hydrogen and is mostly based on repurposed natural gas pipelines. Dedicated H_2 transmission networks are the most feasible option, have the most impact in regard to H_2-CCS chains and have a rather small window of opportunity. The other options are feasible and relevant for decarbonisation as well, possibly independent from H_2-CCS chains. Therefore, they should be pursued as well. At least, immediately relevant actions that are not connected to substantial negative effects or significant costs should be taken, unless inaction closes off options that might well prove to would have been useful. While further research and debate will be necessary on several issues, these immediate actions should not be deferred.