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Authors		
Name	**Organisation**	**E-mail**
Daniel Benrath*	RUB	daniel.benrath@rub.de
Stefan Flamme*	RUB	stefan.flamme@rub.de
Sabrina Glanz*	RUB	sabrina.glanz@rub.de
Franziska Hoffart*	RUB	franziska.hoffart@rub.de

*Mark Lead Author with asterix

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Abstract

Within ELEGANCY, the German case study aims at an accelerated decarbonisation of gas infrastructure via a H_2-CCS chain. To assess options for decarbonisation, the case study focuses on three scenarios for a decarbonised gas infrastructure with carbon capture and transport (CCT) and transport of hydrogen. The interdisciplinary analysis explores the feasibility of different infrastructure options and considers technical, economic, legal and social aspects. Critical issues are identified which define the general framework for a decarbonised gas infrastructure. In the light of the different scenarios, this framework as well as further research on the feasibility of the scenarios in the German case study are briefly analysed.

Technical challenges of the three common CO_2 capture technologies oxyfuel, pre-combustion capture and post-combustion capture as well as the transport of CO_2 are worked out. Subsequently, the technical challenges of a H_2 infrastructure (addition of hydrogen in the natural gas network / separate H_2 network) are discussed.

The economic approach to analyse the different scenarios, which consists of a stakeholder-centred economic assessment of different H_2 and CCS infrastructure options in Germany, is described in more detail.

Legal aspects regarding the feasibility concern regulatory restrictions, costs and barriers and touch different areas of the law (e.g. planning law, procedural law, ecological law, energy market regulation). The law for CCT and H_2 transport differ greatly, especially in regard of clarity and comprehensiveness.

As a framework of the social perspective, the current state of acceptance research on CCS and H_2 technologies as well as on pipeline infrastructure in Germany is reviewed. Based on different models of acceptance, an approach to a suitable systematization of acceptance for the German case study is derived.

TABLE OF CONTENTS

Page

ACT ELEGANCY, Project No 271498, has received funding from DETEC (CH), the German Federal Ministry for Economic Affairs and Energy (DE), RVO (NL), Gassnova (NO), BEIS (UK), Gassco AS and Statoil Petroleum AS, and is cofunded by the European Commission under the Horizon 2020 programme, ACT Grant Agreement No 691712.

1 INTRODUCTION

1.1 Scope of the Case Study

ELEGANCY aims to accelerate the decarbonisation of Europe's energy system by combining carbon capture and storage (CCS) and hydrogen with a full chain H_2-CCS infrastructure linking together Norway, the Netherlands, Switzerland, the UK and Germany. As part of five case studies, the German case study analyses the decarbonisation of the German energy sector. So far, no concepts have been developed for an H_2-CCS chain in Germany. A large-scale transformation of the German infrastructure is needed in order to decarbonise the German sectors energy, industry, mobility and households, which requires large investment decisions. For this purpose, the German case study addresses technological, economic, legal and social aspects that are relevant for three infrastructure scenarios. The German case study will analyse the opportunities of a decentralised decarbonisation infrastructure with carbon capture and transport (CCT) in Germany to depleted gas fields in the Netherlands (scenario I). This scenario will be compared with mixing decarbonised reformed hydrogen from Norway into the existing natural gas grid (scenario II) and with building up a pure H_2 distribution network (scenario III).

1.2 General Background for CCS in Germany

The German energy policy 'Energiekonzept' was passed in 2010 as part of the German energy transition, shortly after the adoption of the EU CCS-Directive in 2009 [Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide (OJ EU 2009 L 140/114), last amended 13 December 2011 (OJ EU 2012 L 26/1)]. In the 'Energiekonzept', CCS is mentioned as one option to reduce CO_2 emissions in Germany. [BMW10] During this time, several CCS activities were planned in Germany. For the most part, these activities were confronted with a sceptical population and were finally stopped due to a multitude of social and economic reasons. [FIS12a] Nevertheless, the CCS research project in Ketzin/Brandenburg has been successfully implemented.

The European CCS-Directive was transferred into the KSpG [Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Kohlendioxid-Speicherungsgesetz), 17 August 2012 (BGBl. I 1726), last amended 20 July 2017 (BGBl. I 2808)] in 2012. Although the KSpG allows for CCS in general, the relevant federal states with the most promising storage sites opted against the possibility of further demonstration of commercial usage of CCS, due to a lack of social acceptance. [FIS12b] While the political development halted any progress of CO_2 storage in Germany, the transport and export of CO_2 for storage abroad is legally possible, but not yet put into practice.

1.3 General Background for H_2 transport in Germany

The introduction of hydrogen as major energy carrier has been discussed in Germany for decades and several initiatives on different levels where launched to further this goal. The government supports the development of hydrogen and fuel cell technology primarily within the cross-departmental 10-year program *National Innovation Programme for Hydrogen and Fuel Cell Technology* (NIP) (German: Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie), launched in 2006. [BMV16, BMVn.d.] The *National Organization for Hydrogen and Fuel Cell Technology GmbH* (NOW - Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie GmbH) was established in 2008 and is in charge of coordinating and managing the *NIP*. [NOWn.d.]

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Whereas the addition of small amounts of hydrogen from biogenic sources in the natural gas network is reality in Germany, no policy steps aiming at an H_2 network were taken yet. There are local pipeline networks for hydrogen, most notably in the Rhine-Ruhr Area as well as at Bitterfeld and Leuna in Eastern Germany, but these networks supply the chemical industry and are primarily used for the exchange of by-product hydrogen.

1.4 References

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2 TECHNICAL CHALLENGES

The focus in this chapter is clearly on the technical challenges of CCS, as this technique is not yet being tested and applied on a large scale in Germany. In addition, the choice of possible capture techniques and detergents is very complex due to the multitude of possibilities.

On the other hand, hydrogen has been used in German industry for decades, and there are already a few commercial pipelines in existence. As a result, the hydrogen infrastructure is considered technically advanced and the technical challenges will be more likely related to route planning and the addition of hydrogen to the existing natural gas network.

2.1 Technical Challenges of Carbon Capture

Scenario I of the German case study examines a decarbonisation of big point sources, such as energy-intensive industry and power plants. Therefore, the three common pathways (Figure 2.1) of carbon capture, oxyfuel, pre-combustion capture (pre-cc) and post-combustion capture (post-cc) are considered as possible ways to capture CO_2. The choice of capture technique depends on various parameters and conditions of the use cases. The two transport ways considered are pipeline transport and ship transport, with decision-making mainly dependent on monetary considerations and transport distance. The storage of CO_2 is supposed to occur in depleted natural gas fields in the Netherlands and thus does not belong to the technical considerations of the German case study.

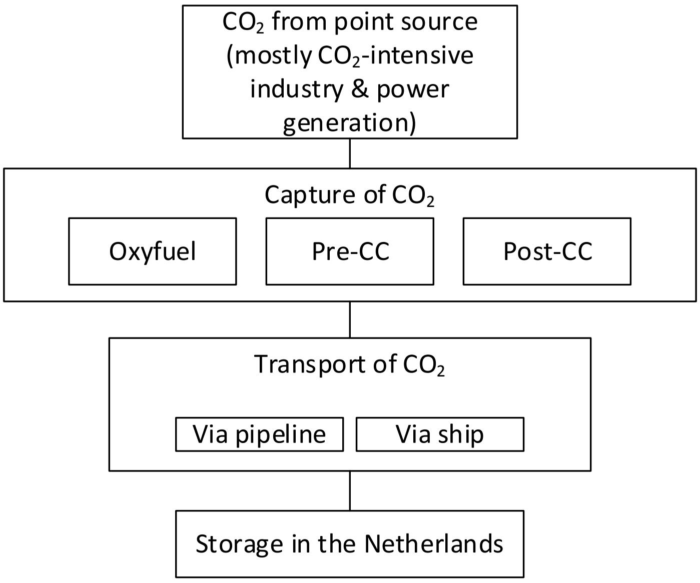

Figure 2.1: Pathways of CCS in the German case study.

2.1.1 Overview of CO_2 Separation Techniques/Detergents

In the following, the separation techniques and detergents are discussed, for the technical challenges of the main categories oxyfuel, pre-cc and post-cc, see chapters 2.1.2 to 2.1.4. The separation techniques and detergents commonly used in the three pathways are shown in Figure 2.2. A detailed description of all capture techniques and detergents displayed in Figure 2.2

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is attached in Appendix A.1. Based on the description of the techniques, the main challenges of oxyfuel, pre-combustion and post-combustion capture are elaborated in the following subchapters.

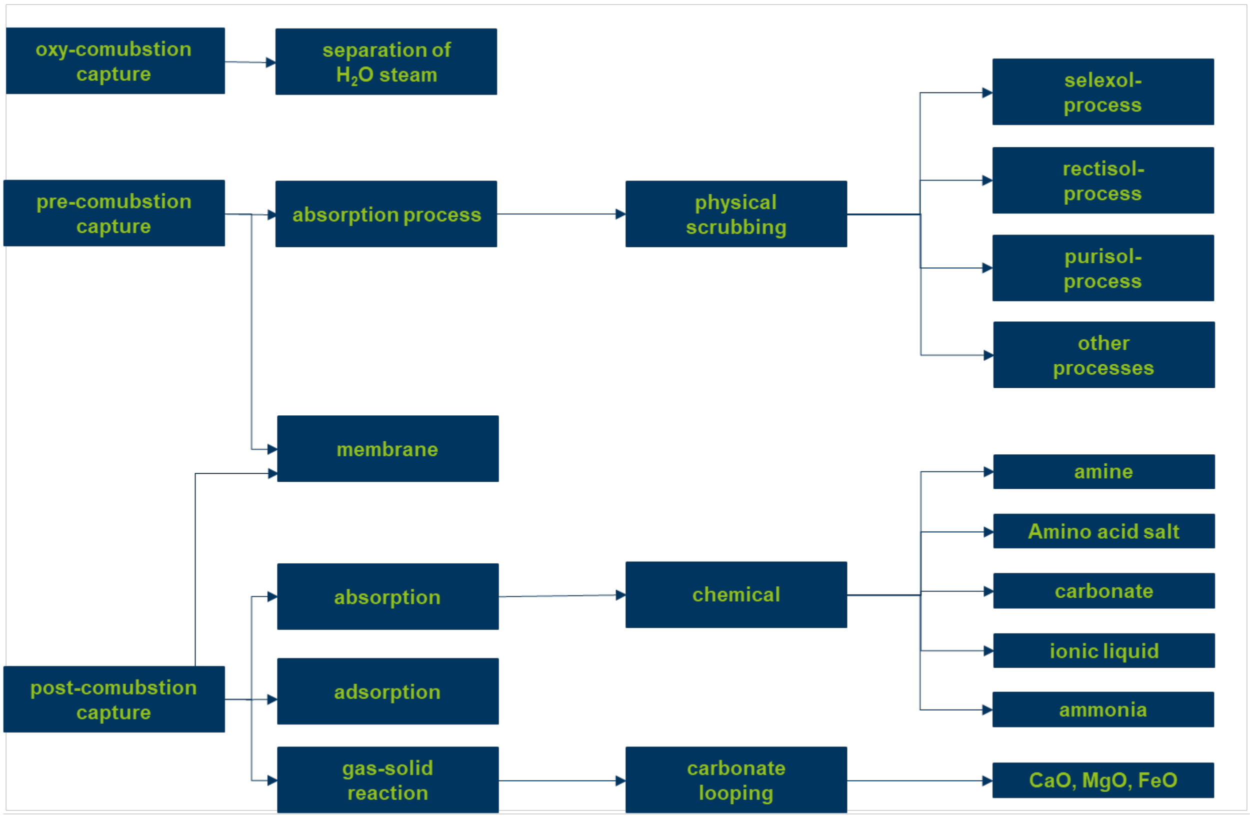

Figure 2.2: Overview of CO_2 capture techniques and detergents.

2.1.2 Technical Challenges of Oxyfuel Combustion

The oxyfuel technique is combustion under a pure oxygen atmosphere that requires energy-intensive air separation. The combustion temperature under this pure oxygen atmosphere would be over 2.000 °C and thus over the thermal stability of most materials. Therefore, a portion of the exhaust stream is being recirculated to cool down the reaction. Due to the high CO_2 concentrations in the exhaust gas flow (almost 90 %), the remaining H_2O can be condensed relatively easy. A technical scheme is attached in A.2.1; Table 2.1 contains data about the variance of power plant parameters due to the oxyfuel technique, as well as the applicability.

Table 2.1: Variance of power plant parameters due to the oxyfuel technique. [DÜR09; GOE09]

Decrease of efficiency (percentage points)	10 %
Increase of costs per MWh	70 %
Capture efficiency	90 %
Max. achievable purity of CO_2	95 %
Retrofitting capability	uncertain
Applicability to fuel types	gas, solid
Pressure of flue gas	~1 bar
Possible capture processes	condensation of H_2O

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The decrease of efficiency of about 10 percentage points and the consequent increase of costs is mostly due to the high energy consumption of the air separation, the exhaust recirculation and the flue gas cleaning. The retrofitting capability is to be further discussed, nevertheless a lot of space is needed for the additional facilities. Oxyfuel can be used with every type of fuel that requires oxygen to burn. The major technical challenges of the oxyfuel combustion are the relatively low purity of the separated CO_2 (95 %), the air separation and the high combustion temperatures. Impurities of up to 5 % are expected in the oxyfuel process. The entry of so-called false air, i.e. not completely pure oxygen, can reduce the CO_2 purity in the flue gas and thus may no longer meet regulations. With increased entry of false air, the concentration of impurities may gradually increase, which may require re-treatment, further reducing efficiency. The main polluters of CO_2 are argon, nitrogen and oxygen with a volume fraction of about 4 %, but also sulfur dioxide with a volume fraction of 0.5 % (see Table 2.4 in 2.1.5).

These additional components in the flue gas mean that not only the properties of pure carbon dioxide can be considered in further processing. If the stream separated from the flue gas would be more than 99 % CO_2 as desired, the gas stream could be liquefied with a pressure increase to 73.8 bar for transport. However, since the other components are subject to other thermodynamic properties, an additional increase in pressure by more than 40 bar must be expected. [KON09] This considerable additional compression is clearly reflected in the energy to be applied and thus the efficiency. The cryogenic air separation plants should reach a purity of the oxygen of 99.5 vol.-%. For this purpose, in the low-temperature range at -182 °C, the oxygen is separated by condensation. Before the air can be fed to the separation column, it must be cleaned of coarse dirt particles and compressed to 5.4 bar. The compaction takes place in a large three-stage compressor with an energy requirement of about 150 MW. This effort alone results in a loss of efficiency of 8 %. However, since the waste heat generated by the work, amounting to 115 MW, can be used to pre-heat condensate in the steam power process, some losses can be absorbed again. [LÖS07; KUC13] Nevertheless, the overall 10 % efficiency loss in oxyfuel-fueled power plants is primarily due to the air separation plants. A further problem in the design of oxyfuel power plants are the high combustion temperatures due to pure oxygen firing. Although the temperature can be reduced to 2,000 °C by recirculating the CO_2-rich flue gas, the materials for the burner and firing chamber must nevertheless be adjusted. [KUC13] Furthermore, in conventional power plants in the event of retrofitting due to the high temperatures and the increased oxygen content, inter alia, heat exchange surfaces, furnace geometry and flue gas catalysts have to be redesigned. In addition, new steam boilers are needed to allow the return of the CO_2-enriched flue gas.

2.1.3 Technical Challenges of Pre-Combustion Capture

The pre-combustion process is based on CO_2 capture before combustion. In this process, a hydrogen-rich synthesis gas is burned, which is produced in an upstream process using a coal gasification. Due to this combination of different processes, power plants that are equipped with the pre-combustion process are also known as Integrated Gasification Combined Cycle (IGCC) power plants. [KON09] A technical scheme is attached in A.2.2; Table 2.2 contains data about the variance of power plant parameters due to the oxyfuel technique, as well as the applicability. Due to the complex separation processes, the efficiency in IGCC power plants drops by about ten percentage points. The CO_2 avoidance costs are about the same as the costs of a generated MWh in a conventional power plant without pre-combustion equipment. The comparison of a coal-fired power plant with a pre-combustion process and the oxyfuel process shows a strong similarity in

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terms of cost and efficiency. Only the CO_2 capture rate of a power plant equipped with oxyfuel separation is five percentage points higher.

Table 2.2: Variance of power plant parameters due to the pre-cc technique. [DÜR09; WIE15]

Decrease of efficiency (percentage points)	8..10 %
Increase of costs per MWh	100 %
Capture efficiency	85 %
Max. achievable purity of CO_2	99 %
Retrofitting capability	uncertain
Applicability to fuel types	solid
Pressure of syngas	30 bar
Possible capture processes	absorption (physical), adsorption, membrane

Most challenges in the pre-combustion process result from combustion with a hydrogen-rich gas, as well as the resulting high combustion temperature. Another important factor is choosing the right carburetor for synthesis gas production. For combustion at up to 1,700 °C, the gas turbines must be designed to fit the hydrogen-rich gas as efficiently as possible. This adaptation is intended to bring about an improvement in the degree of efficiency. In addition, the components of an IGCC power plant must be checked with respect to their corrosion behavior. Combustion with nearly pure hydrogen causes the base materials, which usually have a low chromium content, to be attacked. In addition, as the levels of sulfur, alkalis and vanadium in fuels increase, the demands on surfaces are changing. [CRE07; KUC13; RÜG07]
Depending on the fuel used and the purpose of the synthesis gas to be generated, different reactors can be used for the gasification. These include the fixed bed, fluidized bed and entrained flow reactor. Each of these three reactors offers advantages and disadvantages for various processes which have to be weighed out for optimal design of the power plant. The fixed bed reactor can use the coarsest grain fuel of up to 30 mm grain size. Gasification takes place at temperatures between 800 and 1,000 °C. These temperatures result from the reaction of oxygen with carbon to carbon dioxide. In a further step, the coal is gasified with CO_2 and water vapor. For subsequent drying and decomposition of the coal, the synthesis gas is cooled down to 550 °C. These relatively low temperatures can cause unwanted by-products such as tar, which do not dissolve in the further process. The fluidized bed reactor is suitable for fuel particles with a maximum grain size of 8 mm. In this gasification reactor, mainly highly reactive fuels such as lignite and biomass are gasified. The temperature in the gasifier is based on the fuel used, since the temperature must be below the ash temperature, so that individual particles do not fuse together and thus block the fluidization in the carburetor. For smallest particles of less than 0.1 mm in size or solid particles dissolved in liquid, the entrained flow reactor is suitable. This type of carburetor requires the highest temperatures at 1,400 to 1,900 °C. The resulting slag settles on the inside walls of the reactor. This has the positive effect, that on the one hand the container wall is protected from the synthesis gas, on the other hand, this requires an additional continuous and uniform cooling from the outside. Although flow reactor reactors have an increased oxygen demand due to the temperatures, a carbon conversion degree of over 99 % can be achieved. The gasification can be carried out in all three reactors under both atmospheric and elevated pressure. Since the gas is subsequently to be used for power generation in gas turbines, a pressure level above the gas turbine inlet level is recommended. [OEL15] The key point of the technical challenge is finding the right carburetor for the application. Since not every retrofit power plant is designed for all temperatures, this, as well as the additional power to be provided and the fuel used, must be taken into account in the choice. In addition, the integration of the separation process into an already existing power plant

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proves to be difficult. Due to the high complexity and the combination of different engineering processes, an efficient and secure integration of the plant components is necessary. In order to keep the efficiency as high as possible, a higher integration into the main process makes sense, but the risk of total failure of the entire power plant increases with the failure of a single component. [CRE07]

2.1.4 Technical Challenges of Post-Combustion Capture

The process of CO_2 capture after combustion can be done in many ways. The four main groups are shown in Figure 2.3.

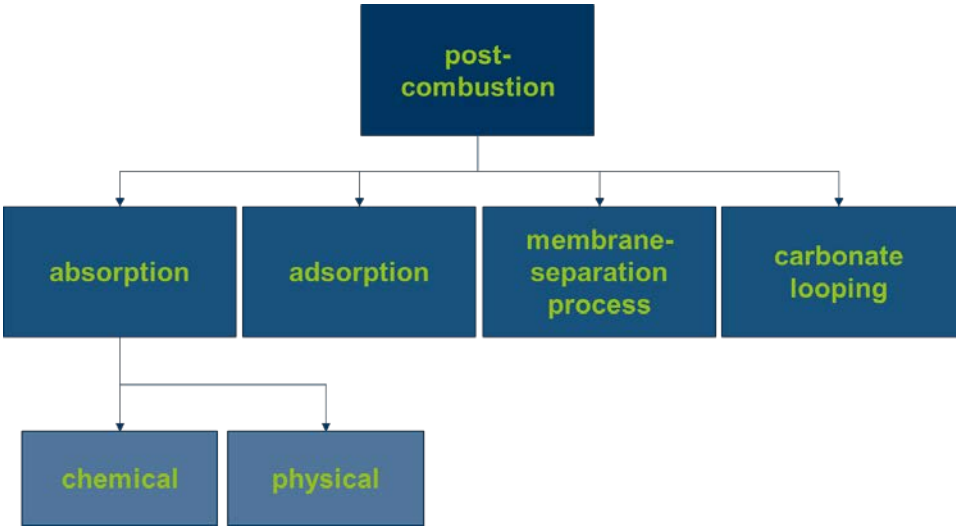

Figure 2.3: Possible separation techniques for post-combustion capture.

The most widely used and therefore the best researched method is currently absorption. This can be further subdivided into chemical and physical absorption, with the chemical absorption, in which the CO_2 is bound in solvents, in most cases being preferred. Another method is adsorption. During adsorption, the CO_2 molecules adhere to the surface of a substance through physical connections and can later be desorbed again. The membrane technique relies on the property of different sizes of molecules, allowing various substances, comparable to a mesh, to be trapped or transmitted by the membrane. The fourth method considered is carbonate looping, where carbon dioxide is collected and released in two passes in natural materials. [FIS15; GRÜ07] The technical schemes are attached in A.2.3; Table 2.3 contains data about the variance of power plant parameters due to the post-combustion technique, as well as the applicability.

Table 2.3: Variance of power plant parameters due to the post-cc technique. [DÜR09; WIE15]

Decrease of efficiency (percentage points)	12 % (absorption); 5-9 % (carbonate looping, membranes)
Increase of costs per MWh	100 %
Capture efficiency	85 %
Max. achievable purity of CO_2	99,9 %
Retrofitting capability	yes
Applicability to fuel types	all
Pressure of flue gas	~ 1bar
Possible capture processes	absorption (physical, chemical), adsorption, membrane, carbonate looping

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The biggest technical challenge in *chemical absorption* is the enormous regeneration effort of the solvent. In order to free the carbon dioxide-laden solvent in the desorber, about 80 % of the total energy requirement is used for flue gas scrubbing. [NOT13] Especially in the amine scrubbing with monoethanolamine the energy consumption is very high. For one kilogram of separated CO_2 around 4 MJ of energy are needed. In order to make regeneration less energy-intensive, the focus of research is on new amine mixtures with a lower heat requirement. Possible mixtures are mixtures of primary and tertiary amines. The tertiary amines have a lower regeneration heat requirement, but also slow down the absorption of CO_2. To counteract this reduced speed, the primary amines are used to act like an accelerator. Since these new compounds are not yet used, their corrosive behavior and their stability to accompanying gases must also be taken into account. [RÜG07] Equally challenging is the general choice of the appropriate detergent for chemical absorption, since it must be decided individually according to the properties and requirements of the process, which is the most efficient and suitable.

In the case of *physical absorption*, the high required pressures represent the central problem. In the absorber, pressures above 20 bar are present. However, the CO_2 in the flue gas of any furnace process has only a partial pressure of about 0.15 bar. [GÖR15] Prior to compressing this flue gas stream means a significant power requirement, which has a negative effect on the efficiency.

The *membrane* process presents two major obstacles. One problem is the low CO_2 concentration in the flue gas and the low total pressure of the feed. Even if only a small amount of CO_2 is contained in the flue gas, the entire volume flow must pass through the membrane. As a result, large membrane areas are required in order to maintain a rapid flow rate. Larger membranes require more space and additionally increase costs. The other obstacle is the pressure gradient required for the separation. In order for the process to run through the membrane, either the flue gas stream is compressed to 10 bar or a vacuum of 0.1 bar is created on the membrane. This pressure change is energy intensive and expensive. [MER10]

Similar to the oxyfuel process, the supply of pure oxygen represents the greatest technical challenge in *carbonate looping*. To bring the temperatures in the calciner to 900 °C, pure oxygen is burned with a raw material. This oxygen is usually provided from a cryogenic air separation plant. The additional effort is also crucial here for the efficiency losses. Alternatively, the calciner can be heated indirectly. For newly created power plants, the required heat can be taken from the steam generator. In the case of retrofittable power plants, on the other hand, another fuel chamber has to be set up. The resulting heat can then be forwarded to the calciner and the resulting flue gas to the carbonator. However, due to the additional amounts of flue gas the efficiency only can increase by about 1.5 percentage points. [EPP15]

The challenge of *adsorption* on solids lies mainly in the simultaneous operation of at least two adsorbers. As the solid alternately adsorbs and desorbs carbon dioxide, thorough cleaning can only be guaranteed if two adsorbers are always used. Should an adsorber fail, the amount of flue gas for the other adsorber doubles. Since these can only absorb a certain amount of CO_2, the flue gas cleaning would not be satisfactory.

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2.1.5 Technical Challenges of CO_2 Transport

As noted before, the purity of the captured CO_2 is a key challenge. Therefore, the pressure required for liquefaction cannot be accurately determined in advance by the different proportions of contaminating accompanying components. What is certain, however, is that the pressure must be increased significantly, which increases the energy to be applied. Table 2.4 shows the amount of contaminating accompanying components in the case of coal and gas power plants for the three capture techniques. As stated before, the impurities are highest in oxyfuel combustion.

Table 2.4: Impurities in flue gas for the three capture techniques, distinguished by coal and natural gas firing. [KUC13]

Capture technique	Component	Coal (Vol.-%)	Natural gas (Vol.-%)
Post-combustion	SO_2	< 0,01	< 0,01
	NO_x	< 0,01	< 0,01
	$N_2/Ar/O_2$	0,01	0,01
Pre-combustion	H_2S	0,01-0,6	< 0,01
	H_2	0,8-2,0	1
	CO	0,03-0,4	0,04
	CH_4	0,01	2
Oxyfuel	SO_2	0,5	< 0,01
	NO_x	0,01	< 0,01
	$N_2/Ar/O_2$	3,7	4,1

For a coal-fired power plant with an electrical output of 1,000 MW, annual CO_2 emissions of around five million tons can be expected. Since CO_2 in the gaseous state has a low density, it must first be liquefied in order to transport such quantities. [GRÜ07] In order to liquefy the CO_2, pressures above the critical point, i.e. at more than 73.8 bar, are aimed for. At this pressure and at temperatures above -50 °C, CO_2 is initially liquid and then supercritical, resembling the density and flow behavior of a liquid and being the most compact to transport. [KUC13] A one-time compression until arrival at the deposit is usually not enough. Also included are the pressure drops during transport, for example, over the distance of a pipeline or through various temporary storages on the way with a ship. In addition to transport and environmental conditions, such as temperature, the purity of CO_2 plays an important role in compression. With additional impurities such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), nitrogen (N_2) as well as argon (Ar), oxygen (O_2) and water the compression work increases significantly due to the different thermodynamic properties. For the additional substances to be compressed, it can be assumed that the pressure increases from 73.8 bar up to 114 bar. [KUC13; MID15; KON09] The aim before transport is therefore to clean the CO_2 again using suitable procedures. The excretion of remaining water is particularly important. If H_2O is present in the pipelines, the risk of corrosion and associated damage increases significantly. [MET05] In order to counteract this effect, for example, an energy-intensive drying of the separated gas should be added to the treatment process in order to eliminate the water. Likewise, negative influence on the transport materials exert SO_2 and H_2S in connection with CO_2. As these form acids in combination with one another, the risk of corrosion increases as well. [KUC13; MID15]

But the liquefaction of almost pure carbon dioxide is also problematic. Since CO_2 is mainly compressed in the supercritical state, it has both liquid and gaseous properties. However, this results in the problem that it is too liquid for the pressure increase with compressors and too gaseous with pumps. The most effective method is the combined use of compressors and pumps.

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It is important to convert the CO_2 as quickly as possible into the liquid state, because there the energy consumption for further compression is much lower. To achieve this and to overcome the large pressure difference of about 100 bar, a multi-stage compression process is recommended. Because the pressure increase in addition to the density and the temperature increases, intercooling is recommended. The effect of the temperature increase is much more pronounced even in the gaseous state than in the liquid state. Which type of pumps and compressors (turbo, radial, axial) is used must be decided individually and calculated using specific process parameters. [SCH15]

2.1.6 Evaluation and Priority Setting of the CCT Challenges

In the following, the aforementioned technical challenges are to be sorted into a four-field matrix (see Figure 2.4) using two criteria. The challenges are assessed on the one hand based on the complexity of the technical implementation and on the other hand on the relevance for process efficiency. Here, only the challenges of the separation processes are considered, since the transport, the retrofitting ability and flexibility have no direct effects on the capture process. On the basis of the division into the four fields, it can be discussed in the following, at which points the most or least need for action exists.

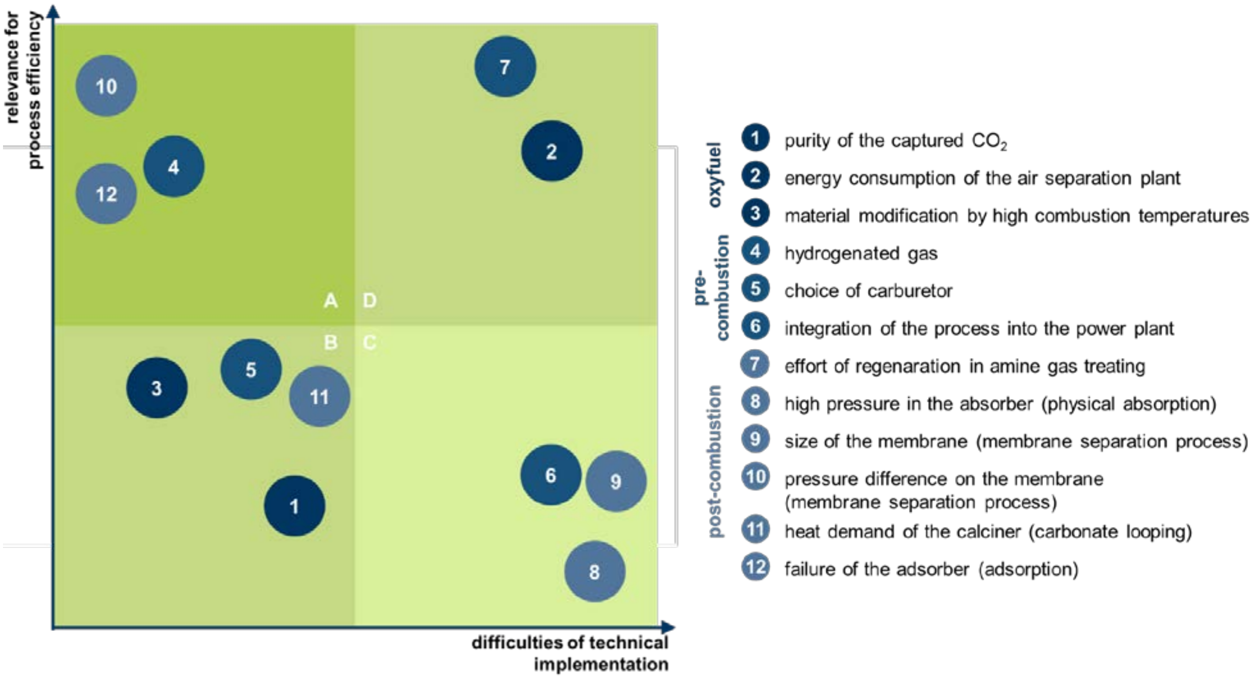

Figure 2.4: Classification of the technical challenges.

It should be noted that the challenges of the individual processes, pre- and post-combustion as well as oxyfuel are compared within the processes, but the divisions are not to be understood across procedures. The fields are named from top left counterclockwise from A to D. After the division into the four-field matrix, a strategy has to be considered for the fields. It makes sense to decide which implementations of the challenges should be the focus. The focus of research and development should be on the challenges in field A. There can be created with the least technical effort of the greatest benefit. On the other hand, the challenges in field C have to be postponed first, because a high technical difficulty of implementation is only of minor relevance for process efficiency. For fields B and D, depending on the two evaluation criteria, no direct statement can be made as to which areas should be given preferential treatment. For this, the economic efficiency

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and monetary aspects have to be included. It should be considered whether a high technical effort for the process pays off, or whether the effort exceeds the benefit too much. If this is the case, initially smaller process improvements with low R&D requirements are preferable.

A complete description of the assignments in the matrix can be found in the appendix A.3.

2.1.7 Repercussions on the Case Study

Flue gas of most furnaces is under environmental pressure, production processes have higher pressures and higher CO_2 concentrations: [MET05]

Gas turbines:	3 - 4 % vol.
Coal:	12 - 14 % vol.
Gas fired boiler plants:	7 - 10 % vol.
Methanol production:	10 % vol.
Blast-furnace gas:	20 - 27 % vol.
Cement kilns:	14 - 33 % vol.
Ammonia production:	18 % vol.
H_2 production:	15 - 20 % vol.
Natural gas processing:	2 - 65 % vol.

Thus, the first three very low values would be indicators that for energy applications in the case of retrofitting CCS the use of chemical absorption would be a sensible option. For processes with higher partial pressures, a physical absorption would also be feasible. In general, the choice of the associated CO_2 emitters should, from a technical point of view, be based primarily on their emission quantity and secondarily on the prevailing CO_2 partial pressure.

Figure 2.4 gives an overview of capture technologies, which are most likely to be used in the three main categories of oxyfuel, pre-combustion, and post-combustion.

Process	Oxyfuel	Pre-CC	Post-CC
Chemical absorption			
Physical absorption			
Adsorption			
Membrane			
Carbonate looping			
Condensation of other components			

process of choice

process possible, but not economic

process in development

process not relevant

Figure 2.5: Assignment of the capture processes to the main categories. - Based on [GÖR2015]

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2.2 Technical Challenges of a Hydrogen Infrastructure

In the following, the technical challenges of a hydrogen infrastructure are elaborated. As mentioned before, from a technological view, the hydrogen infrastructure in Germany is much more advanced than CCS technology. However, the addition of higher amounts of hydrogen to the existing gas grid is still in the test phase and requires further investigation. Therefore, the thermodynamic changes that are caused by such a mixture will be worked out below, as well as the effects on gas users. Finally, the conditions of a separate H_2 network and the current status are shown. It must be pointed out from the beginning that most of the detailed challenges of a hydrogen infrastructure will emerge later in the case study, especially when it comes to the detailed planning of the infrastructure. Therefore, this chapter is just an introduction to the topic.
The final components of the H_2 chain in the German case study are yet to be defined in the further process of the work. Based on the actual state of information, Figure 2.6 shows, how the H_2 chain in the German case study could look like.

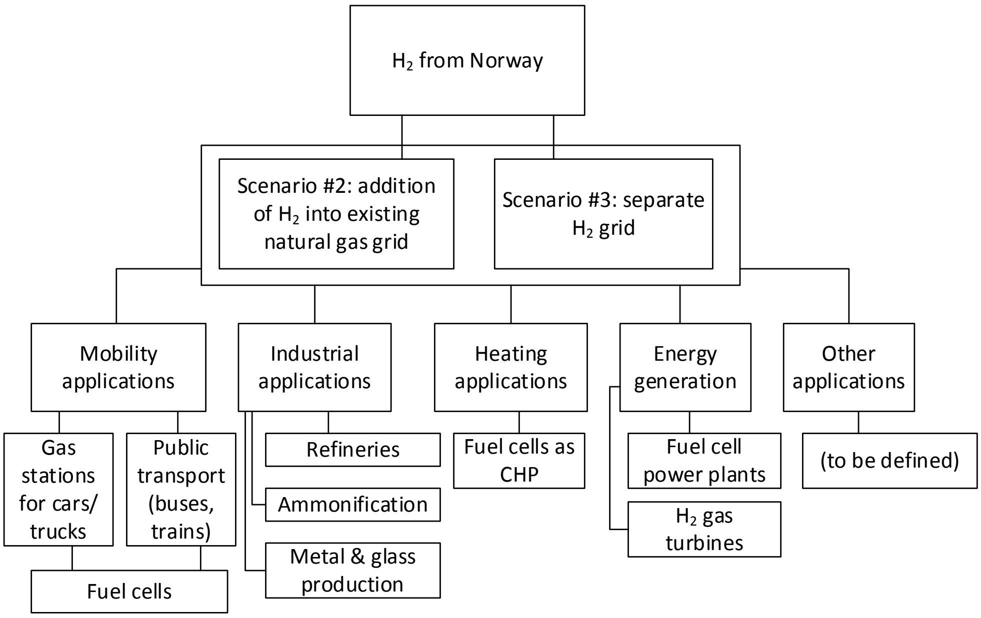

Figure 2.6: Possible H_2 chain for the German case study.

2.2.1 Addition of H_2 into Natural Gas Grid

The restrictions of the existing limits for the addition of hydrogen into the natural gas grid are specified in DVGW worksheets G 260 and G 262 [NIT15]. In the past, city gas was fed in (up to 50 % by volume of H_2), which is why systems for H_2-rich gases have to comply with DVGW Worksheet G 260 Gas Family 1. Table 2.5 shows the compositions of urban and natural gas.

Table 2.5: Composition of natural gas (H&L) and city gas (1960&1990). [MÜL13]

		CH_4	N_2	H_2	CO	CO_2	O_2	Hydrocarbons
Natural gas	H-quality	96	2	-	-	1	-	1
	L-quality	88	11	-	-	1	-	-
City gas	1960	18	7	55	16	3,5	0,3	0,2

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	1990	25	25	32	15	2	0,5	0,5

A great amount of regulations focusses on the injection of hydrogen into the natural gas network, as this will provide the easiest way to store and transport the gas. Today, around 10 % of the gas in the natural gas network could be replaced by hydrogen without damaging the system. On the other hand, equipment such as gas fuel stations might not be able to cope with this amount and restrict the percentage further down to 2 % [VAL11]. The main problems are a change in the gas characteristics and the sensitivity of the pipeline material to hydrogen. A direct injection of synthetic gas would not have such limits, as the main component of natural gas is as well methane. However, to produce such high amounts of syngas, enormous amounts of carbon dioxide would be needed and it is not yet sure if this can be made available from environmental-friendly sources.

2.2.1.1 Changes of gas properties of a mixture of natural gas and hydrogen

When adding hydrogen to the natural gas network, the following things must be considered:
Hydrogen can affect the material properties. For H_2-susceptible materials, however, it does not matter whether a high or low concentration H_2 is present in the natural gas. The frequency of damage can be compensated by moderate additional costs in the form of monitoring and maintenance. Nevertheless, gas losses through permeation or leaks can occur. However, the density of H_2 is lower, so this problem can be classified as low and has little influence on H_2 amounts < 20%.

According to DVGW worksheets G 260 & 262, three conditions must be fulfilled for hydrogen feeds: [MÜL13]

Wobbe index*:	> 13.6 kWh/m³
Relative density:	> 0.55
H_2 content:	< 10 % by volume

*: The Wobbe index is a corrected calorific value, which should make it possible to equalize the burning behavior of different gases. Gases with the same or a very similar Wobbe index can be exchanged for one another without any structural changes to burners or nozzles of gas appliances.

The following Figure 2.7 shows the change in gas quality as a function of the H_2 concentration. The lower limit of the calorific value is reached with an addition of 30 vol.-% hydrogen to the Holland-L gas. Concerning the Wobbe index, even amounts of 50 % hydrogen would be theoretically possible. The specified minimum density (d = 0.55) of the mixture is reached for Holland L and North Sea H gas with about 15 vol.-% hydrogen and for Russian natural gas already with an addition of 3 vol.-% hydrogen.

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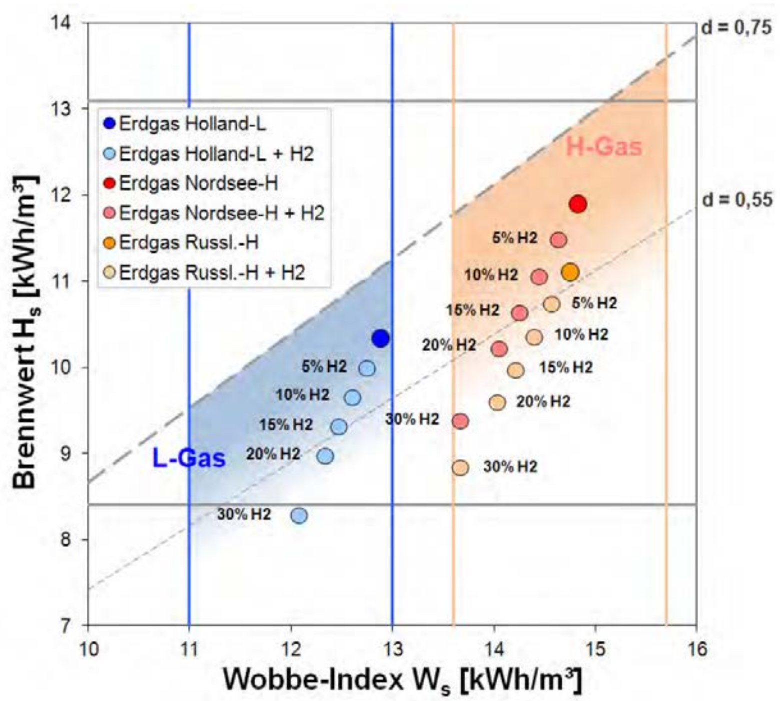

Figure 2.7: Change of the gas properties (Wobbe index, calorific value, realive density) in dependence of the H_2 concentration for three different natural gases. - Taken from [MÜL13]

In the figures below, the percentage change in transport capacity and pressure loss is plotted linearly with the H_2 concentration.

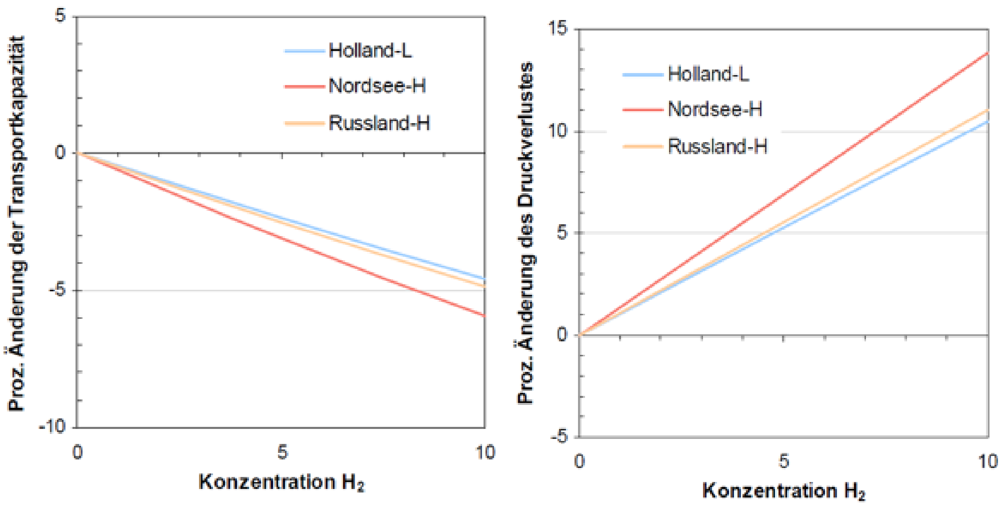

Figure 2.8: Percentage change in transport capacity (left) and pressure losses (right), depending on H_2 concentration for three different natural gases. - Taken from [MÜL2013]

The figure on the left shows that an addition of 10 vol.-% of hydrogen at similar pressure drops results in 5 to 6 % loss of transport capacity, which is less than the difference between the three natural gases. The pressure losses (graph on the right) caused by adding 10 vol.-% of hydrogen are between 11 and 14 %. That means, to bring the gas mixture to the initial pressure, an increase

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in compression work of about 25 to 32 % is necessary. However, based on the energy content of the gas, the additional energy for a 500 km transport distance would be less than 1 %. [MÜL13] Furthermore, these changes in thermodynamic properties of the gas mixture have to be considered [MÜL13]:

- Methane number is reduced (5-7 units) (methane number of natural gas must not be too small, it corresponds to the percentage volume fraction of CH_4)
- Flame speed increases (H_2 concentrations in the fuel gas increase the flame propagation speed, if it rises above the critical value it leads to a flashback)
- Ignition limits are widened
- Calorific value is reduced
- The mixture's heating value only drops slightly
- Calorific value of natural gas is important for billing: Determined according to DIN EN ISO 6976

Hydrogen is already partially fed into the German natural gas grid, mostly from biogenic sources. Over 8,000 biogas plants are currently installed in Germany, which induce 104,660 cubic meters of biological methane per hour into the gas network. Known injections points for hydrogen can be found at:

- Falkenhagen, Brandenburg with around 360 m^3 H_2/h
- Hamburg-Reitbrook with around 220 m^3 H_2/h
- Frankfurt with around 60 m^3 H_2/h
- Prenzlau with around 120 m^3 H_2/h
- Mainz-Hechtsheim with a maximum of 1,200 m^3 H_2/h

A.4.1 contains additional tables with properties of several mixtures of hydrogen and natural gas.

2.2.1.2 Applications of mixtures of natural gas with hydrogen

According to the DVGW, H_2 concentrations of less than 10% by volume for end devices in the natural gas network are to be assessed as uncritical if the technical data for firing according to DVGW-AB G 260 are complied with. Furthermore, DIN EN 437 applies to all gas appliances in the public gas supply, which installations with natural gas H prescribe a test gas (G 222) with an H_2 content of 23 vol.-%. In households there may be older devices that are not suitable for concentrations greater than 10 % by volume. In the project NATURALHY, the emission trends of two recent gas burners (2006 & 2008) and one older one (1993) were investigated. It turned out that with all three burners a stable combustion process with the addition of H_2 is possible. In one of the newer burners, a power of 10 kW is possible with an addition of 50 vol.-% of H_2 and with an addition of 85 vol.-% of H_2 a power of 5 kW is possible. The other new gas burners show a stable combustion up to 75 vol.-% H_2 in natural gas. However, it turns out that if these concentrations are added, the emission values (CO, CO_2, NO_x) will improve considerably. Thus, the CO and CO_2 content in the exhaust gas with an addition of 70 vol.-% H_2 is reduced by half. The NOx levels have dropped by a total of 85 %. Boiler bed efficiency and oxygen content in the flue gas are doubled. In the older gas burner stable operation is possible with an admixture of up to 40 vol.-%. This also improves the emission levels and the net efficiency increases by 1.5 times. [MÜL13]

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In a completed project of DVGW "G1-02-12", the entire natural gas supply chain of a small town was tested for hydrogen tolerance of up to 10 vol.-%. For this new fuel new value zones had to be set up. Though, the volume-weighted calorific value was determined according to DVGW G 685. On the one hand a device with the test gas G 222 with 23 vol.-% hydrogen, on the other household appliances (condensing boiler, storage water heaters, stove burners, etc.) up to 30 vol.-% H_2 were investigated. There were no abnormalities or disturbances of the equipment. Furthermore, the gas quality was investigated. It became clear that there are hardly noticeable changes in the calorific value or Wobbe index due to the admixture. The feed can be realized with natural gas flow rates of up to 20 Nm^3/h. It is limited by the calibration limit of the hydrogen meter at 0.376 Nm^3/h and by the working range of the inlet pressure regulator. The extensive laboratory investigations did not give any indication of the restrictions that make existing hydrogen supply limits in DVGW worksheets G 260 and G 262 necessary. The laboratory tests with household appliances have already been carried out by different companies up to an admixture of 30 % by volume. [MÜL13]

Natural gas fueling stations are connected directly to the natural gas grid. The table below shows requirements for natural gas for use as fuel. According to the fuel standard DIN 52624 there is a maximum admixture of 2 vol.-% H_2 for gas engines. Therefore, this value limits the addition of hydrogen into a natural gas grid that is connected with natural gas fueling stations. There are no significant problems and compliance with engine-specific methane numbers at H_2 levels of up to 20 % by volume. An increased H_2 content has a positive effect on the combustion properties, reduces pollutant emissions and creates a torque deficit. With a natural gas H_2 mixture of 40:60 the torque decreases by 10 %. However, the tank material of natural gas steel tanks in cars, 34CrMo4, is only suitable for H_2 if the maximum tensile strength is less than or equal to 950 MPa, otherwise there is a risk of material embrittlement. [MÜL13]

Table 2.6: Requirements to gas composition for natural gas as fuel. [MÜL13]

Gas properties	Unit	Min.	Max.
Calorific value (natural gas H)	MJ/kg	46	-
Calorific value (natural gas L)	MJ/kg	39	-
H_2 concentration	vol.-%	-	2
Methane number	-	70	-

In gas turbines, premix burners can be damaged if hydrogen is added to the natural gas network. Therefore, the limit here is between 1 and 5 vol.-% H_2. For larger hydrogen concentrations, new gas turbines need to be developed. In September 2012, Siemens declared its industrial gas turbine with premix burner up to 50 MW_{el} suitable for H_2 contents up to 15 vol.-%. In the compressor, the flow rate must be increased due to the lower energy content of the H_2 admixture, which requires more drive power. The flow rates must be adjusted and the operating pressure must be checked. Otherwise, by connecting a fuel gas methanation, the hydrogen can be converted to methane. Ultrasonic, turbine and bellows meters are suitable for high hydrogen concentrations, however, the density must be adjusted. Volume converters can be operated without restrictions for hydrogen volume fractions of up to 10 %. With admixtures of 50 vol.-% H_2, there are only deviations of less than 0.1 %. Accordingly, a subsequent correction must be carried out. There must be a revaluation from the operating to standard state. As a result, the K-number is measured and determined by DVGW-AB G 486. [MÜL13]

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Gas pressure regulators are planned according to DVGW Ab G 491 and operated in accordance with DVGW AB G 260 and can use H_2-containing gases up to 67 vol.-%. Measuring systems are planned according to DVGW AB G 492. Its scope of application also refers to DVGW AB G 260. Gas measurements shall comply with provisions of DVGW AB G 685 regarding calorific value determination during the accounting period. These require that the average calorific value may not deviate more than 2 % of the calorific value during the billing period. Fuel cells have problems with strongly fluctuating natural gas compositions with H_2 fractions, but fewer problems with high but constant H_2 fractions. Furthermore, Stirling engines either have partially no function or the efficiency is reduced by 5 percentage points. In industrial applications, it is not the hydrogen in the natural gas network that causes problems, but the fluctuating gas quality. In addition, hydrogen may have to be removed from the fuel gas in some applications. [MÜL13]

Finally, the figure below gives an overview of the H_2 tolerances of different applications. A distinction is made between the safe admixture of hydrogen (green), the need for adaptation (yellow) and regulation and the need for research (blue). [MÜL13] The figure shows, that most applications tolerate at least 10 % of hydrogen and in a few cases, an adaption is needed.

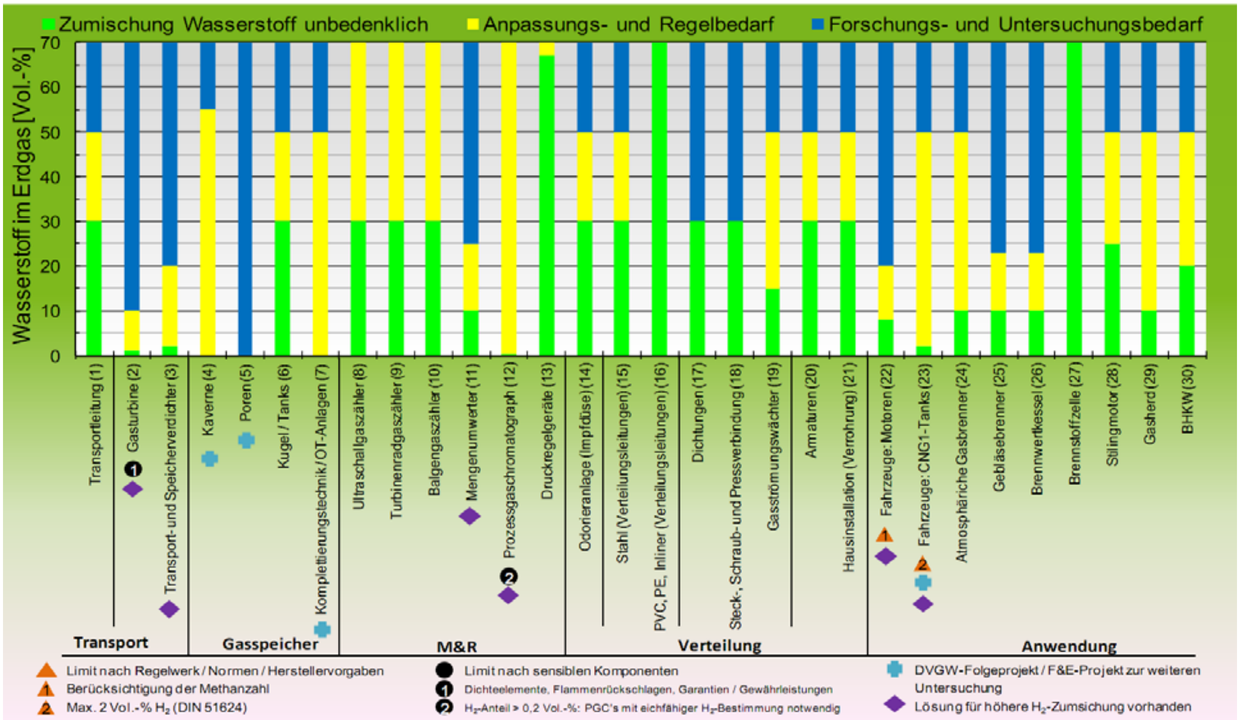

Figure 2.9: Hydrogen tolerances of several natural gas appliances. – Taken from [MÜL13]

2.2.2 Separate H_2 Grid

As already mentioned, pure hydrogen infrastructures are already technologically advanced and have been in practice for decades. The technical challenges lie in the detailed planning of such infrastructures as well as the replacement or adaption of natural gas applications to pure hydrogen, but not in the technology itself.

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2.2.2.1 Application of pure hydrogen

The production of hydrogen in Germany totaled to an amount of 21.5 billion m^3 in 2007 [MAI07]. Newer studies estimate a hydrogen production of 86.76 billion m^3 in Europe in 2011 [ADO17]. Around 50 % of the total hydrogen production is being consumed by refineries and 32 % by the ammonia industry. 6 % of the hydrogen is used in metal processing and less than 1 % for liquefaction. [STI16] By the end of 2017, there will be around 50 hydrogen refueling stations, by 2023 even 400 refueling stations. [DWV17] Which sectors and applications of pure hydrogen will be part of the German case study has to be decided in the further process.

2.2.2.2 Transport of hydrogen

Today, only 5 % of the hydrogen is transported, with the remaining 95 % produced locally [STI16]. The main actors in this area are Air Liquide and Linde in Germany, which are owning and maintaining the second biggest hydrogen pipeline system in Europe with a length of around 385 kilometers [STE07A]. Air Liquide acquired a pipeline and filling station in the Ruhr area in 1993 that was built in 1938 and has been in operation since then. The total length of the pipeline sums up to around 240 km and 14 production sites are connected to it, whereas four of them are suppliers. The currently connected producers are Bayer AG, Degussa AG and Ruhrkohle Bergbau AG. The total capacity is estimated to be around 250 million m^3 of hydrogen per year. The purity of the transported hydrogen amounts to 99.95 % [GWI14]. In eastern Germany another pipeline system is located. The network Leuna-Bitterfeld belongs to Linde Gas AG and has a total length of 135 km. The system connects the hydrogen production from Linde in Leuna to different consumers such as the Total refinery in Spergau and the Linde filling station for trailers. Furthermore, the pipeline of Dow/BSL between Buna and Böhlen is connected to the system. Other small pipelines are in operation, such as in Wilhelmshaven with around 12 km. [STE07A]

If not with pipelines, the transport of hydrogen is mostly done by truck [DWV17]. Hydrogen has a low volumetric energy density, which is why the transport takes place in compressed form as a gas, cooled as a liquid or chemically bound in metal hydrides. The individual transport options differ with regard to the required infrastructure, the fixed and variable operating costs, the energy expenditure and the transport capacity. Accordingly, different options are to be favored depending on the transport task. The graph below shows the minimum H_2 transport costs as a function of throughput and distance and thus the transport option to be favored. [GWI14]

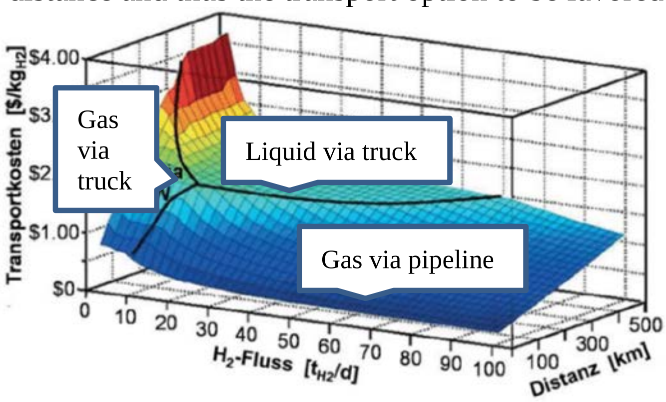

Figure 2.10: Minimum hydrogen transport costs depending on throughput and distance. [GWI14]

It becomes clear that truck gas transport is relevant for smaller amounts of H_2 and short distances. During liquefaction, there is a high fixed cost component in the liquefaction itself. However, the

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transport volume is higher by truck than in the gaseous state, so that this transport choice is relevant for small quantities and longer distances. When transporting via pipeline, large costs are incurred through the pipeline itself. The costs are therefore proportional to the transport distance. For long distances, the pipeline is the most cost-effective alternative. [GWI14]

2.2.2.3 Storage of hydrogen

Pure hydrogen can be stored in salt caverns, which are artificially created cavities in salt flats. Their typical volume is 500,000 m^3 with a pressure range of 60 to 200 bar, so they can store about 5,000 t H_2 (170 GWh). This type of storage of hydrogen is only possible where suitable salt formations exist. The lead time is around 10 years and includes, among other things, a permit, test drilling, solution mining, completion and initial filling. Salt caverns are well suited for seasonal storage because their storage capacity costs are low. [STI16]

Regarding liquefication, Germany inhabits one of only three European liquefication plants, operated by Linde in Ingolstadt. A second liquefier is operated in Leuna and together a liquefication capacity of 26 metric tons a day can be reached [STE07A]. The compressed or liquefied hydrogen is transported to a large part by trailers. Most gas companies own trailers that transport the gas at a pressure of 200 to 300 bars, carrying approximately 2,000 to 6,200 m^3 of hydrogen. Around 1,000 compressed gas tube trailers are in operation in Europe as of 2007. Trucks for liquid hydrogen have a capacity of 15,000; 41000 or 53000 liters, transporting over 6 times more hydrogen than a compressed gas trailer. Around 30 trucks for liquefied hydrogen are in operation in Europe as of 2007. [STE07A; GWI14]

The storage of liquid hydrogen LH_2 is state of the art. In addition, hydrogen can be stored in pore stores. For this purpose, the tightness must be checked and there is a risk of bacterial growth and sulfur production, since hydrogen is a good substrate for sulfate-reducing bacteria. This is one reason why cavern storage is better suited than pore storage because its surface area is repressing bacterial growth. [MÜL13] Hydrogen can also be recycled directly or stored. Due to the low density of the hydrogen and thus also the storage density, the density of the gas must first be increased. On the one hand, hydrogen can be compressed to high pressures or, on the other hand, cooled down to liquefaction. However, the storage densities are still lower than in conventional fuels. The hydrogen can be adsorptively applied to various carriers, which then chemically bind the hydrogen and release it again if necessary. For example, so-called Metal Organic Frameworks (MOF) are being studied as a storage option. Also in the development phase are liquid hydrogen carriers such as the Liquid Hydrogen Carriers (LOHC). Furthermore, hydrogen can be reacted with carbon dioxide to formic acid and then released again when needed. In addition, the hydrogen can be added to fuels, since so the storage density is higher, such as fed into the natural gas grid. Today, there is a maximum hydrogen content of 5 vol.-% from biogenic sources in the natural gas grid. From a thermodynamic point of view, the feed into the natural gas network has a good overall efficiency, but there is a limited absorption capacity. This solution represents a transitional solution to the fossil energy supply. When the power supply switches to renewables, other storage technologies must be used. [MÜL12] In addition, hydrogen can be converted into synthetic natural gas and then fed into the natural gas grid. The production costs of PtG and PtL are less than 10 ct/kWh. [MÜL13]

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3 ECONOMIC PERSPECTIVE

3.1 Research Concept

3.1.1 Research Objective and Approach

The transformation of the German infrastructure in order to decarbonise the German gas grid, industry, transportation and households requires large investment decisions. From an economic perspective, the primary objective of this study is to assess the economic aspects related to the transition towards a low-carbon economy by evaluating the different infrastructure options (scenario I to III) as well as the questions that arise by implementing a possible H_2-CCS chain in Germany.

In short, the economic analysis consists of a stakeholder-centred economic assessment of different H_2 and CCS infrastructure options in Germany. In particular, the economic issues and incentives are examined that are essential in identifying attractive and sustainable opportunities for relevant stakeholders. In this context, the costs and benefits for different stakeholder groups at the different stages of the transition process as well as their influence on political decisions are considered to play a key role for the successful implementation of a new infrastructure. In addition, the macroeconomic background of the different infrastructure options is analysed, including the political environment, the policy framework and the international cooperation and interaction with relevant partners.

This approach is based on the assumptions derived from complexity economics. Contrary to neoclassical economics, in complexity economics, the economy is not understood as a system in equilibrium but instead as an adaptive, complex system. An adaptive complex system is described as a dynamic network of different agents who adjust their behaviour according to their interactions with other agents. In adaptive complex systems, such as the economy, it is hardly possible to identify and implement optimal policies through central planning. [ROO15]

Applied to ELEGANCY, this assumption means that large-scale projects which affect the society as a whole, such as the reorganisation or implementation of infrastructure, cannot be successfully implemented in a democracy and market economy by the political decision of a central planner. The decision for a large-scale project as well as the implementation depends on the various individual decisions made by different actors.

These actors are individual agents who have different interests, views and perceptions about society and economy that often diverge. 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.

The conventional (neoclassical) economic approach neglects these decisive non-economic aspects and executes a classical cost-benefits analysis (CBA), which serves as a basis for assessing the desirability of the different options. However, there is the risk that once a decision is made by a central planner that is based on a CBA, the implementation will be interrupted or even stopped due to protests by the negatively affected stakeholder groups. Hence, it is argued that different actors and stakeholder groups are of great importance for the successful transformation to a decarbonised infrastructure.

Based on these assumptions, the different infrastructure options will be analysed from a German perspective within an extended stakeholder-centred CBA that includes both economic and non-economic aspects. This stakeholder-centred economic approach takes into consideration the costs and benefits for the different stakeholder groups at various states of the transition process as well

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as their influence on political decision-making. It combines conventional neoclassical elements with new elements derived from complexity economics.
This approach is mainly qualitative, containing some descriptive and normative aspects. It is not intended to collect data at his stage of research. The aim is to develop a framework for evaluating different infrastructure options on a meta-level, which can be applied to different large-scale projects. This approach is selected with the intention to direct the process of decision-making and implementation into the desired direction by taking the stakeholder's different interests and influences into account. For this purpose, bottom-up policy recommendations are considered to be the appropriate political response, including participatory measurements.
While the engineer's objective in the case study is to identify and plan the technologically optimal H_2-CCS chain, the economic analysis aims to identify the most realistic option that is to be implemented within the technological feasibility. However, the best technical solution is not always the option that is finally implemented – due to the fact that the optimal technical solution is not per se the optimal solution for society.
In the initial project phase, the main task concerns the economic evaluation of different infrastructure options and aims to reasonably narrow down the research objective. Since the described approach represents an extension of the conventional approach, conceptual research is required. This chosen approach identifies an infrastructure option that is both technological feasible and desirable from an economic and societal perspective and which might not be the first best option.
The research objective is divided into two consecutive research questions:

1) *How can relevant stakeholders of different infrastructure options be identified? What are their interests and potential influence? What possible scenarios arise from these considerations?*

2) *What are the requirements for successful implementation of a specific infrastructure option? What consequences and effects can be expected?*

Since these research questions are no yes-no questions, an overview of possible scenarios summarizes the range of options and related conditions as well as the requirements. In this sense, the analysis can be understood as a critical assessment from different perspectives, which shows possible pathways rather than precise projections of future development. Instead of recommending an optimal solution, the analysis aims at raising awareness for economic and societal factors that facilitate or impede the implementation of the available infrastructure. The intention is to highlight the effects and mechanisms related to different infrastructure options and framework conditions. This process also includes developing possible scenarios since the future development of framework conditions shape the pace for the transition towards a low-carbon economy. In order to develop possible scenarios, projections about the future development are often needed, such as the future energy demand, market potentials, or demographic data. It is crucial to mention that these projections need to be understood as rough estimates rather than concrete prognosis.
In addition, there is the need to coordinate with other work packages within ELEGANCY, especially WP 3, which also has an economic focus.

3.1.2 Current State of Literature

In academic economic research, publication in economic journal about general environmental issues and related topics, such as climate change, sustainability and mitigation measures, are rare compared to topics like the financial crisis or even niche topics like schooling. Hence, it is hardly

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possible to find economic articles focusing on technology related topics such as CCS and H_2-CCS chains.

This absence of such articles can be explained by the current critique on general economic research. Applied economic research, especially at the interdisciplinary boundary concerning social relevant research, is not considered to be the main objective of academic research literature and thus often neglected [ROO16].

Available literature, however, mainly focuses on a conventional approach and mostly applies a monetary valuation in the form of a CBA, while often neglecting non-economic aspects. Where the available economic literature is mainly about CSS technologies, there is almost no literature on hydrogen technologies. In general, economic aspects of relevant H_2 and CCS technologies are mainly integrated into accompanying research within an interdisciplinary handbook on a specific topic [e.g. FIN 2015]. Stakeholder-centred CBA is not established. Although, the importance of stakeholder groups for the success of environmental measures is often mentioned in preliminary sections.

Furthermore, there is a variety of research studies on CCS and hydrogen technologies available. These studies are mainly commissioned by the German government or the industry sector and written by research institutes, such as e.g. the *Forschungszentrum Jülich*. Within these studies, economic aspects are mostly included in the form of costs and (future) market potential [e.g. JOA08, BMU16, GER18]

3.2 Intermediate Results

3.2.1 Key Questions

The following key questions have been identified as relevant for assessing the three infrastructure options and for accelerating the transition to a low carbon future. As previously stated, different possible scenarios will be developed for this purpose and critically assessed.

<u>Conceptual key questions</u>

- Which conditions will be relevant for stakeholders to accept and support new infrastructure options?
- What kind of (economic) incentives are required so that relevant stakeholders make the necessary investments?
- Who will be in charge of financing the infrastructure? Which actor will oversee the new infrastructure?
- Will CO_2 be traded as a good in the sense of a recyclable material or will it be traded as a waste product?
- How could a possible H_2/CO_2 market be defined? Who will be the traders? In what sense do these markets differ from other existing energy markets?
- How can a sustainable infrastructure be defined? What are the criteria for a sustainable infrastructure?
- Under which conditions could an infrastructure option be economically desirable? What are the decisive criteria?
- What are the criteria for an economically desirable infrastructure?

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Framework specific key questions

- How will the energy economy develop over time with regard to e.g. energy prices, energy mix and energy demand?
- How will the macroeconomic framework develop with regard to e.g. GDP and interest rate?
- How will the European political environment develop with regard to e.g. CO_2 prices?
- How will the political environment develop with regard to e.g. coal energy phase out, e-mobility, planning security?
- How will public opinion develop in regards to environmental consciousness, sustainable lifestyle, and awareness of climate change?

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3.2.2 Possible Evaluation Criteria

As it is the aim to evaluate the three infrastructure options, an extended variety of criteria are needed in order to also include non-economic aspects in an appropriate way. The following table represents a first collection of possible categories and criteria. In the next steps of research, a final set of criteria has to be selected and modified. While it is reasonable to choose different categories, the number of criteria need to be limited in order to fit the scope of the analysis. Furthermore, it is up for discussion, if these criteria will be represented in monetary terms and what units are adequate to describe the criteria.

Table 3.1: Catalogue of possible categories and criteria

Category	Criteria
Finance	Investment -, operating-, maintenance costs
	Funding opportunities
Sustainability	CO_2 abatement costs
	Value of avoided CO_2 emissions
	Contribute to the protection of the environment
	Potential for emission reduction
	Resilience, future sustainability
Energy	Influence on energy prices
	Emitted CO_2 per unit of energy
	Effect on energy trilemma index
Risks	Health risks
	Dependencies
	potential for individual resistance
Economy	Potential for market leadership and pioneer position
	Creation of new jobs
	Effect on national economic activities /GDP
	Effect on the dependence on fossil fuels
Society	Limitation for personal liberties, intervention in daily life
	Influence on mental and physical well-being

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4 LEGAL PERSPECTIVE

The contribution of the legal team to the German case study is aimed at several goals. At the centre, it delivers the legal background for the case study. This encompasses general aspects of the legal framework of H_2 and CCT infrastructure as well as specific legal aspects of the case analysed in the study. Additionally, the legal team supports the formulation of policy recommendations based on the findings of the overall analysis. For the next phase of research, it will focus on the tasks which are not dependent on prior analyses.

The legal discussion of a CCT infrastructure from North Rhine-Westphalia to the Netherlands pursuant to scenario I is the base for the further legal analysis. This analysis will be mirrored, modified and partially amended to fit scenario III and the introduction of an H_2 infrastructure. The discussion of feeding-in hydrogen into the natural gas infrastructure pursuant to scenario II sees only view legal issues, which are partially very specific; thus, the legal contribution regarding scenario II is rather marginal.

4.1 Legal Aspects of Case Study

4.1.1 Legal Restrictions

Legal restriction for infrastructure on different levels shape possible business decisions and thus the actual costs of an infrastructure project. These restrictions may address the location of the pathways and the details of the technical realisation. Legal restriction for infrastructure in regard of the scenarios of the case may include:

- Technical restrictions and requirements, especially for safety reasons
- Environmental law restrictions, especially concerning areas of special protection
- Requirements stemming from general and special planning
- Contractual obligations, especially concerning the re-use of existing infrastructure on third party land and when crossing third party infrastructure
- Obligations of network operators, especially concerning the re-use of existing infrastructure (and the details of the prior authorisation) or the feeding-in of additional substances

Not all relevant legal restrictions are strict but are the result of considering and weighting different interests.

For the further analysis, the most relevant restrictions and their legal base have to be determined. Regarding the weighting of interests, the most relevant interests in the scenarios have to be identified and criteria for their weighting have to be developed. Then, the consequences of the restrictions for the business case options and the remaining margin have to be described.

4.1.2 Planning Procedure: Costs and Risks

Different costs and risks at different stages are connected to the planning procedure required before beginning the operation of a pipeline infrastructure. Especially the time needed for the procedure and the risks of delay can be decisive for assessing business cases. Legal aspects concerning costs and risks of the planning procedure include:

- Actual duration and costs of preparing the administrative procedure
- Legally induced and actual duration and costs of the administrative procedure
- Risks of failure, especially risks and consequences of third party litigation
- Requirements, costs and risks of expropriation

For a specific analysis, the possible procedural regimes and their delimitation have to be worked out. Then, legally induced costs and risks for the different procedures and scenarios have to be

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identified and assessed. The analysis has to take into account how the stakeholders can shape the costs and risks with a special focus on the different consequences of re-using existing infrastructure or creating a new one.

4.1.3 (Energy) Market Law and Investment

The traditional network based energy market is heavily regulated to counter the effect of natural monopolies and to safeguard security of supply. Some of this regulation is (or might become) applicable to the infrastructure envisaged in the scenarios of the case study. As the regulation limits the business options for investors and operators, it may have a negative effect on the investment environment. Aspects of market law with possible negative effects on the investment environment include:

- Restrictions on cooperation of network operators and other market participants (unbundling/cartel law)
- Duties and costs of operators, such as maintenance, access to the network, liability, interoperability of different networks and ultimately disposal
- For scenario II: tariffs and access regime for fed-in hydrogen; taking into account costs of adjusting network for calculating tariffs

The market situation of the nascent and respectively emerging markets of CCT and pipeline based hydrogen supply differ in many ways from the traditional network based energy market, which partially mirrors in a different regime. For the further analysis, the actually and prospectively applicable regulation for these markets has to be identified and its possible impacts on the investment environment have to be discussed. In a further step, it can be analysed how far the regulation fits the special context of the case study scenarios.

4.1.4 Cross-Border Infrastructure

All three scenarios of the case study depend on cross-border transport. The cross-border situation can address different legal aspects. Additionally, this situation evokes practical barriers, which can be and partially actually are solved or mitigated legally. Finally, the interaction of different jurisdictions can add further complexity to some legal problems of trade and transport. For the case study, such cross-border issues can include:

- Trade rules of the internal market (or a lack thereof)
- Different markets due to different national regulation, especially concerning grey, low carbon and green hydrogen
- Technical harmonisation for transport and border crossing (or a lack thereof), especially in comparison with the natural gas system
- Legal options for guaranteeing production, transport and reception to tackle coordination failures in an interdependent chain
- Investor protection in an interdependent chain of production, transport and reception
- Restrictions on the export (or import) of CO_2 respectively hydrogen, especially taking into account the different levels of international environmental law, EU internal market law and national law

The legal issues concerning cross-border infrastructure demand different perspectives for the further analysis. Especially the multi-level dimension of the cross-border context is connected to very different legal discussions. First, the rules for cross-border infrastructure have to be identified and analysed. Secondly, the possible tensions connected to different legal spheres have to be taken into account. Thirdly, the possible tensions between the different legal levels have to be analysed.

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But not only existing rules and their tensions are relevant in this context. Additionally, it has to be discussed, which actual problems connected to the cross-border transport can (or even have) to be addressed legally.

4.1.5 Regulation and Barriers

The introduction of a new infrastructure (as well as a general shift in the use of an existing one) meets many obstacles and barriers on different levels (different to those already mentioned). Some of these barriers are tied to the regulatory background as they could be addressed by appropriate regulation or even result from the regulation itself. These barriers can be discussed on a legal level and can include in regard of the case study:

- Legal uncertainty or legal frictions regarding the applicable rules, especially in regard of the H_2 pipeline regime in face of mixed production and usages
- Interaction of CCT and emission trading
- Discrimination of certain technologies, e.g. hydrogen as energy carrier, such as in regard of tariffs, transmission regime, access regime, staid aid and tax

The challenge in regard of these points is to identify relevant regulatory barriers and to understand their legal context. Based on this and further analysis on policy needs, ways to mitigate or even resolve these barriers can be discussed.

4.1.6 Legal Background of Policy Perspectives

At this stage of the case study, a deeper legal analysis of policy options would rather be moot. But the legal background of further policy recommendations can be prepared to steer the policy discussion. Different policy issues have to be addressed at different levels and there are legal restrictions for new regulation that cannot easily be removed. Aspects of this legal background can include:

- State aid regime of the European Union
- Cartel law in regard of investor cooperation
- Fundamental rights as limit to regulate business
- Competences for different regimes

4.2 Draft Assessment of Relevant Legal Background

In regard of scenario I, the relevant legal background for CCT infrastructure is prominently found in the KSpG. Transposing the CCS-Directive, the regime for the construction and operation of a CCT pipeline resembles the regime for a natural gas pipeline in most aspects and explicitly allows the cross-border transport. Thus although CCS in Germany is politically ruled out, there is a rather rich and favourable legal environment for CCT. But some issues remain unresolved. Especially, the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972 (as amended in 2006) ("London Protocol") is applicable to the export of CO_2 for dumping into the seabed, possibly ruling out the export of CO_2 as envisaged in scenario I. Additionally, as the rules have never been put to test by practice, there may be further frictions and problems at different levels.

In regard of scenario II, there are well established and practically proven rules for feeding-in electrolysed hydrogen into the natural gas infrastructure. But the regime for reformed hydrogen remains unclear. Additionally, the specific problems arising from large scale feeding-in and adjusting the network to rising concentration are not addressed by the current regime and experience.

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For (partly) energetic H_2 pipeline networks pursuant to scenario III, there is today no clear legal regime suitable for investment. Although electrolysed hydrogen is considered gas in the light of the EnWG [Gesetz über die Elektrizitäts- und Gasversorgung – Energiewirtschaftsgesetz, 7 July 2005 (BGBl. I 1970, 3621), last amendment 20 July 2017 (BGBl. I 2808)], reformed hydrogen is not covered and the consequences for a pure H_2 pipeline network are not certain. Any discussion on this has to consider the existing general pipeline and competition law as well as the rules for natural gas networks as a blueprint for prospective legislation or as a debatable legal base.

4.3 State of Discussion and Need for Research

Many of the legal aspects relevant for the case study are subject of an extensive discussion in the context of natural gas infrastructure. This research has to be assessed and adjusted to the case study.

In regard of the specific discussion on CCT in Germany, the legal research focused on more general points and the legal aspects of storage. Since CCS was virtually ruled out by political decision, the legal discussion on CCT has muted down. There is only punctual research on the legal aspects of CCT in Germany and a need for further research in this field in the light of the case study. On the EU law and international law level, there is some discussion on CCT; especially harmonisation and the export of CO_2 in the light of the London Protocol have been discussed. This discussion is the base for further research in the specific context of the case study.

In regard of feeding-in hydrogen into the natural gas network, there is only limited research predominantly focusing on issues of promotion schemes for renewable energy and power to gas for energy storage. As the concentration of H_2 was considered to be technically limited, there is no substantive research on the legal aspects of raising the concentration.

In regard of energetic H_2 pipeline networks, there is no substantive discussion in legal research. This may change with the further development of H_2 filling stations in combination with the existing industrial H_2 pipeline networks. So far, most of the specific legal research on H_2 pipelines needed for the case study will be genuine.

4.4 Research Question and Focus

At the next phase, the research for the legal contribution to the German case study aims to determine and analyse the legal background for the studied business cases. Thus, the research will map general restrictions and barriers for the scenarios, restrictions for infrastructure pathways and the costs and risks involved for different options. Additionally, the legal margin for policy development is discussed. The results of this phase will help to define the final design for the case study and prepare the specific case study as well as the final policy recommendations.

As the contribution of the legal team will not be able to provide an extensive discussion and analysis of all relevant legal aspects, one of the major challenges will be to set gainful focuses. The criteria for these focuses align with available research results and the needs for a realistic case study and effective policy recommendations. Accordingly, the focuses will shift due to progress and results of further research within and without ELEGANCY, technical and economic challenges and needs, changes in the legal background and the evolving goal and details of the case study. Especially, the coordination with WP3 and WP4 may specify the scope of the legal contribution to the German case study or turn the spotlight to certain points.

For now, the research of the legal team for the German case study will focus on:

- Constraints for pathways

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- Adjustment of infrastructure law to CCT and H_2 transport, especially in regard of legal handling of innovative technologies
- Impacts of legal costs and risks – especially in regard of litigation – on overall costs
- Comparison of the legal consequences of using an existing infrastructure or creating a new one
- Frictions in the cross-border transport, especially – in coordination with WP3 – concerning international environmental law (London Protocol)

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5 SOCIAL PERSPECTIVE

Social acceptance is a key factor for the successful implementation of new technologies. In the past, especially energy technologies such as large-scale infrastructure projects or perceived risk technologies have evoked conflicts and protests in the population. With this in mind, the German case study includes social acceptance of the scenarios by employing a sociological perspective. Among others, the restructuring and expansion of gas infrastructure, the installation of a new (pipeline) infrastructure to transport CO_2 respectively H_2, the transport of CO_2 and H_2 and the use of H_2 as a new energy carrier are measures which impact social acceptance in regard of the implementation of the scenarios I to III. The empirical study will identify chances and risks for public acceptance of the scenarios and its components in the German population and aims at working out possible approaches to their implementation.

Up to now, the acceptance of a decarbonised gas infrastructure via a H_2-CCS chain has not been explored. The study will be based on the current state of acceptance research on CCS and H_2 technologies as well as on pipeline infrastructure in general and will focus on the following aspects:

- State of awareness and knowledge regarding CCS and H_2 technologies and pipeline infrastructure in the German population
- Technology perception including social, economic and ecological dimensions
- Factors affecting the acceptance

5.1 State of Research on Social Perception

5.1.1 State of Research on Social Perception of CCS

The research field of public perception of CCS is rather young as the first scientific article was published in 2002. [LOR14] Since 2006, several research projects on social perception of CCS in the German population were conducted.[1] They were mainly implemented by the German institutes Fraunhofer Institute ISI, Forschungszentrum Jülich (IEK-STE) and the Wuppertal Institute for Climate, Environment and Energy. [DÜT15] In 2012 and 2015, items measuring knowledge, familiarity and attitudes regarding CCS were part of the yearly panel on the acceptance of the energy system transformation, performed by the IEK-STE. [SCH12a] In 2011, the Special Eurobarometer (364) [EUR11] contained a section on 'Public Awareness and Acceptance of CO_2 capture and storage'. Besides, many international studies, e.g. in the United States, the United Kingdom, Sweden, Japan [overview in LOR14] as well as in neighbouring countries, e.g. in Switzerland and the Netherlands have been realised. [WAL11; BES09] Hence there is a broad data basis for further research on social acceptance of CO_2 transportation in Germany.

The main results of previous studies on acceptance in the German population indicate rather little acceptance of CCS technologies. At the same time the level of awareness and knowledge of as well as familiarity with CCS technologies is rather low. [DÜT15; PIE15] Nevertheless, there is no general nationwide refusal of CCS, as shown by the successful project implementation in Ketzin. [DÜT15]

[1] E.g. "Sozioökonomische Begleitforschung zur gesellschaftlichen Akzeptanz von Carbon Capture and Storage (CCS) auf nationaler und internationaler Ebene" (2006 to 2007), "Scrutinizing the impact of CCS communication on the general and local public" (2009 to 2010) and "CCS-Chancen" (2012 to 2014)

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Trust in relevant stakeholders, perceived risks and benefits were the main determinants of social acceptance of CCS. Specifically, risks were estimated rather high, while benefits were perceived as rather low. [DÜT15; LOR14; SCH12] According to the Eurobarometer [EUR11], perceived risks of CCS located in the neighbourhood (within 5km) mainly related to environmental and health issues, followed by fear of leaks and concerns regarding the safety of the CO_2 transport to the storage site. Regarding perceived benefits, German respondents – compared to participants from other European countries – viewed CCS least effective to fight climate change and expected the fewest benefits of a CCS implementation in their region. If benefits were expected, they mainly concerned the improvement of air quality and the creation of new jobs. [EUR11]
Respondents showed more trust in stakeholders representing NGOs and science than they had in stakeholders representing industry and economy. Concerning the intended purpose of CCS projects, research projects were more accepted than industrial projects. [DÜT15; OLT12; EUR11]
Different technical scenarios and siting contexts related to differing ratings of social acceptance. For example, coal fired plants were less accepted than biomass or industrial exhaust emissions as a CO_2 source. [DÜT16] Storage of CO_2 found little approval both onshore and offshore, yet the acceptance was a bit higher for offshore storage among people who did not live near the coast. Also people were more willing to protest against onshore projects than against offshore projects. Finally, CO_2 segregation was more accepted than transport and transport was more accepted than storage. [DÜT15; PIE15]
More information and discussion about CCS led to a more negative assessment of the technology. [PIE12; PIE10] While discussing CCS within a focus group, the participants became more concerned about the safety of carbon storage. [SCH12] Information about regional risks (environmental, financial liability) and chances, the location of the site, funding, technical feasibility and emergency schedules were defined as most relevant to the formation of opinions regarding a CCS project. Participation at an early stage e.g. in the form of open-ended discussions as well as transparency and confidence building during the process increase the chance of higher acceptance. [DÜT15]
Besides, socio-demographic characteristics correlated with risk perception and acceptance of CCS: women showed a higher risk perception and gave more negative valuations than men. [PIE15] In Switzerland, the framing of CCS as either opposed to or supplementing renewable energy technologies was a relevant factor for acceptance. [WAL11]
Summarizing, the acceptance of CCS projects is rather low, but at the same time depends on the respective context. For the German case study, especially the acceptance of CO_2 transport is of relevance which seems to be higher than the acceptance of CCS in its entirety.

5.1.2 State of Research on Social Perception of H_2 Technologies

Several national and international studies on acceptance of H_2 technologies have been performed in the last years, mainly focusing on H_2 mobility. HyTrust (2009-2013) and HyTrustPlus (2014-2016) were initiated as socio-scientific research projects to accompany the German Federal Government's National Innovation Programme (NIP). Further studies examined social acceptance of hydrogen fuel cells, H_2 mobility and its infrastructure (e.g. H_2 fuel stations) in several European countries. H_2 technologies have mostly been evaluated neutral to positive, while participants' knowledge of, familiarity and experience with these technologies was rather low. [HYA17; ZIM12; ACH10; HEI08; HUI15] In eight European cities[2], most people would have preferred H_2

[2]Amsterdam, Barcelona, Berlin, Hamburg, London, Luxembourg, Madrid and Reykjavik

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buses over conventional buses, but a need for more information was stated. [HEI08] Respondents in Germany and several European countries[3] revealed a moderate familiarity with fuel cell electric vehicles (FCEV), but little knowledge and few experience with the technology. [ZIM12; HYA17] Hydrogen fuel cells in private homes were less known than fuel cells in mobility. [HYA17] Only few respondents were aware of a H_2 station in their city, but the majority would have supported the construction of a fuel cell power station as well as the installation of a H_2 station in their city. [HYA17] Huijts et al. [HUI15] found the Dutch population to approve the implementation of H_2 fuel stations, although this positive attitude was limited by the NIMBY effect. [HUI15]

Overall, perceived benefits were rated higher than the perceived costs and potential risks were assessed as rather low. [HYA17; ZIM12] Less need of petrol, less CO_2 emissions and the H_2 price were viewed as the most important positive impacts of H_2 vehicles. Regarding Micro Combined Heat and Power, respondents gave a moderate to positive evaluation on eco friendliness, user friendliness, usefulness and security. The most negative impacts were seen in the need of new infrastructure, costs induced by its implementation and the immaturity of the technology. [HYA17] Only few studies analysed the acceptance of hydrogen without focusing on one of the previous fields of application. In doing so, Schmidt et al. [SCH16] found independence from central power grid and potential of decentralisation/energy independence to be relevant factors for the acceptance of hydrogen. [SCH16]

In relation to other energy technologies, H_2 technologies were more accepted than conventional energy technologies, but less accepted than renewable energy technologies. Except for Germany, electric vehicles or hybrid vehicles were valued higher than FCEVs. [HYA17] Besides, differentiating between green hydrogen and hydrogen produced by using conventional technologies proved decisive for acceptance. Green hydrogen was met with high acceptance while hydrogen produced from fossil energy sources was valued more critical. [ZIM12] Most people endorsed owning and/or buying H_2 technologies (FCEVs, fuel cell facility) in the future on condition that they serve their purpose equal to conventional technologies (costs, possibilities to fill up). [HYA17] Finally, young and higher educated men were the most supportive of hydrogen technologies in the Netherlands [ACH10], while in another study psychological variables were found to be more relevant than socio-demographic or spatial variables. [HUI15]

All in all, H_2 technologies, above all H_2 mobility, experienced rather high acceptance. However, many aspects concerning acceptance of H_2 technologies still need to be examined, e.g. the expansion of H_2 infrastructure.

5.1.3 State of Research on Social Perception of Pipeline Infrastructure

Acceptance of CO_2 pipelines has been analysed as part of the CCS process. [e.g. SCH17a] In contrast to CO_2 pipelines, H_2 pipelines already exist in Germany. Nevertheless, to the authors' knowledge there are no studies on the social acceptance of installing a new H_2 (pipeline) infrastructure available yet. Referring to comparable pipeline infrastructure such as natural gas pipelines or mineral oil pipelines, few studies with a focus on communication strategies can be found. A key success factor for the implementation of the natural gas pipeline OPAL in Eastern Germany was interactive communication. [SAS15] The comprehensive participation process that accompanied the building of the pipeline CONNECT by Shell Rheinland Refinery led to adaptions demanded by the social environment (closed construction, bypass of the natural reserve) and enabled the implementation. [KRE16]

[3] Belgium, France, Norway, Slovenia, Spain and UK

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Representative data in Germany revealed a low level of knowledge regarding for example the overall length of existing pipelines for natural gas and mineral oil, the existence of CO_2 pipelines worldwide and the costs of CO_2 transportation via pipeline compared to train or lorry. [SCH17a] The personal and societal risk of a CO_2 pipeline as well as the general attitudes were evaluated neutrally. The involvement of environmental organizations and convincing safety concepts were found to be crucial factors for public acceptance of a CO_2 pipeline in the own neighbourhood, while financial participation, financial compensation and participation in the planning process were less relevant. [SCH17a] A neutral evaluation and limited knowledge has also been exposed by focus groups that were interviewed to examine the public perception of CO_2 transportation in pipelines in the UK. Key concerns were related to perceived risks, the safety and the "first-of-a-kind" nature of CO_2 pipelines. [GOU14]
Although CO_2 pipelines are comparable to natural gas pipelines, there are differences relevant for public perception: on the one hand, CO_2 pipelines are often first-of-a-kind, on the other hand, CO_2 as transported product is not directly seen as a benefit by people. [NOO14]
For the German case study, it is assumed that a beneficial perception of the transported product may be a key factor for the acceptance of the pipeline. Besides, it can be assumed that the construction of new pipeline infrastructure will be met with less acceptance than the use of already existing infrastructure.

5.2 Research Concept

5.2.1 Public Perception of Energy Technologies

Research on social technology acceptance implies the analysis of its origin, forms and effects in societies. Differentiation of everyday technology, technology at work and external technology (large-scale technology/external risk technology and infrastructure) approved to be an effective classification for a more precise analysis. Compared to everyday technology and technology at work, external technologies evoke the highest refusal. This is above all ascribed ambivalent perceptions considering risks and benefits and their distributive justice. [SCH17] Based on knowledge, interests and values, controversial perceptions of risks and benefits are causing technology conflicts. [REN97] Energy technologies mainly apply to external technologies, but on the application level – like hydrogen mobility and fuel cells for private homes – are also classed among everyday technology.
Acceptance of large-scale projects can be defined as active or passive approval and ranges from support/engagement, approval and indifference to toleration, rejection and resistance. [ZOE09] It is reflected in social actors' attitudes and behaviour and is measured at a particular time. [SCH15]
To study public perception of energy technologies, several models of acceptance with sociological and/or psychological focus have been elaborated. Much noticed is the technology acceptance framework by Huijts et al. [HUI12]. Relevant factors according to the technology acceptance are knowledge, experience, trust, fairness, affects, perceived costs, perceived risks, perceived benefits, outcome efficacy, problem perception, norms and perceived behaviour control. L'Orange Seigo et al. [LOR14] applied the acceptance framework on CCS technologies. Therefore, they excluded personal and social norms as relevant factors, assuming that CCS is too unfamiliar and unknown for established norms. Considering that the current energy mix and available alternatives are relevant factors for the acceptance of CCS, they added the factor energy mix. Besides they found 'interference with nature' to be a relevant predictor for acceptance. [LOR14]
For a more detailed analysis of acceptance, its breakdown in different categories is helpful. To analyse social perception of the German industry, Schönauer [SCH17] classified acceptance in

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acceptance of objectives, acceptance of outputs and acceptance of outcomes. [SCH17] A similar distinction is further exemplified in a study using the differentiation of several levels to measure acceptance of renewable energy technologies. [HIL18]

Transferred to the German case study, following systematization of acceptance can be identified:

Table 5.1: Systematization of acceptance; authors' own illustration based on [HIL18; SCH17; [LOR14]; HUI12; ZOE11]

	Levels of Acceptance	**Categories of acceptance**	**Factors of acceptance**
Range of acceptance Support, engagement, approval, indifference, toleration, rejection, resistance	Acceptance of decarbonisation by H_2 technologies and CCS as part of the energy transition with taking account of the subject's relevance/importance on the individual level	Objectives	Problem perception Energy mix Available alternatives
	Acceptance of its implementation and economic, ecological and social consequences (e.g. building up a new (pipeline) infrastructure, modification of infrastructure for gas transport and usage, transport of CO_2 and H_2 via pipelines, decarbonisation at major point sources, hydrogen as energy carrier)	Outcomes	Perceived costs, Perceived risks, Perceived benefits Affects Personal/ social norms Outcome efficacy
	Acceptance of implementation and its consequences in the own neighbourhood/on the individual level		
	Acceptance of the procedure and output	Output	Fairness Trust Perceived behavioural control
	Acceptance of relevant stakeholder	Output	Trust Fairness
Context			Knowledge Experience Socio-demographics Spatiality (prevailing) Ideas/beliefs

5.2.2 Acceptance of Relatively Unknown and Unfamiliar Energy Technologies

Information and (scientific) knowledge about technologies do not automatically guarantee acceptance. Nevertheless, they are crucial in order to enable people to evaluate technologies and conceive reliable opinions. As CCS and H_2 technologies are quite unknown and unfamiliar in the German population, methods of typical opinion surveys would rather lead to unstable pseudo-opinions than to reliable attitudes. [BES09; WAL11] The stop/decline of CCS projects in Germany

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in the last years leads to the assumption that knowledge and awareness of CCS is even lower than in preceding studies.

Focus groups and the Information-Choice Questionnaire (ICQ) are established methods to deal with unknown and unfamiliar technologies. Ter Mors et al. [TER13] analysed the quality of resulting opinions of CCS technology contrasting focus groups and ICQ[4] and approved both to be promising methods to gather public opinions. ICQ was attested higher quality regarding consistency, stability and confidence of the attitudes and proved to be a good way to enable respondents to form an opinion. Nevertheless, respondents' opinion keeps highly dependent on the information provided. [TER13]

5.2.3 Prospect

There have been several studies on acceptance of CCS as well as on H_2 technologies, mainly H_2 mobility in the German population and few studies on pipeline infrastructure. The acceptance of a comprehensive decarbonisation infrastructure, including the construction of a H_2 grid and the capture and transport of CO_2, has not been explored yet and will be the contribution of the current study. The analysis will include acceptance of the technology and its infrastructural consequences in general as well as the consumer's acceptance of H_2 as a new energy carrier. Technical, ecological, economic and social aspects will be considered. Therefore, a mixed-methods-design will be applied to the analysis of social acceptance. Explorative interviews are planed with relevant stakeholders that reflect different objectives, interests and motivations. On that account, stakeholders that are located at interfaces between research, politics, industry and society are of interest, e.g. political players, environmental organisations, industrial associations, operators, scientists and citizens' initiatives. By these interviews, attitudes as well as knowledge and experience of experts can be conceived. Several stakeholders can be seen as multiplicators which are crucial for the formation and progress of social debates on external technologies. [REN97] Finally, representative data will be gathered by a quantitative online survey of public acceptance in the German population ($N \approx 1{,}000$).

The little knowledge and awareness of the technologies in the population is a challenging factor which will be responded to via the ICQ method. Attitudes and acceptance towards the scenarios will be measured, providing all information on attributes of the scenarios that are needed to conceive well-considered and well-informed opinions. It will be taken into account that the opinions are dependent of the provided information. By analysing the social acceptance of the scenarios, implications for the way of decision-making and communication strategies will be derived.

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[4] First, respondents received relevant expert information about the technology, including general information as well as information concerning specific scenarios and their consequences. After the information part, respondents evaluated the consequence's importance, (dis)advantage and range of (dis)advantage. Finally, respondents evaluated their general opinion of the technology [TER13].

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A TECHNICAL APPENDIX

A.1 Description of the Main CCS Separation Techniques and Solvents

The separation of CO_2 from the exhaust gas in the ***oxyfuel process*** (see chapter 2.1.2) can be done simply by ***condensation*** of the remaining H_2O, since the amount of CO_2 in the flue gas is almost 90 %.

The ***physical absorption***, which is used mainly in ***pre-combustion capture*** (see Chapter 2.1.3), requires high CO_2 partial pressures. The detergents used are primarily *Rectisol*, *Selexol*, *Purisol* and Fluor Solvent. In contrast to the chemical absorption, the flue gases do not enter into a chemical bond but a physical bond with the solution, usually through the van der Waals forces. [BEH15] The goal of physical absorption, also physisorption, is to exert stronger physical forces on the gas to be absorbed than the forces of condensation. To achieve this, low temperatures and high partial pressures of the gas are sought. [HÜB15] The required high partial pressures are the reason why physical washes are preferred in power plants with pre-combustion technology. However, if the high cost of compressing the partial pressure is accepted, then there are some advantages over the chemical absorption. Since the solvents can absorb more CO_2 at high pressures, the circulation rate is lower, resulting in lower refill with fresh detergent. In addition, no chemical bonds must be broken during the regeneration, which significantly reduces the energy requirement. Due to the lack of chemical bonds, the detergent can be used for a longer time because it is not attacked and damaged. In addition, physical detergents are non-toxic and thus environmentally friendly and cause much less corrosion than chemical agents. They are very flexible and can be adapted to the requirements. Physical flue gas scrubbing is widely used in the purification of synthesis gases. [BEH15; HEI15] Already in the 1950s, the *Rectisol* process was developed and is thus the first physical absorption based on an organic solvent. The methanol used for washing is suitable due to the high selectivity between H_2S and CO_2. Methanol is volatile. Since pressures in the absorber are above 20 bar, the resulting solvent loss must be prevented by cooling to -40 to -60 °C. This methanol convinces with the property that it maintains its viscosity and thus the heat and mass transfer despite the low temperatures. However, the cooling leads to high operating and investment costs. [BEH15] When washing with *Selexol*, polyethylene glycol dimethyl ether (DMPEG) is used as a detergent. This detergent convinces with high thermal and chemical stability. In addition, it is non-toxic and can be biodegraded after being withdrawn from the process in exchange for fresh funds. DMPEG has a low vapor pressure, which reduces the volatility compared to other detergents and can be used simultaneously at temperatures up to 175 °C. Since it has a particularly good selectivity of H_2S over CO_2, it can be used very well for the separation of CO_2 from acid gas phase components, for example in the treatment of natural gas and synthesis gas. [BEH15] For the Purisol wash, a mixture of N-methyl-2-pyrrolidone (NMP) and water is used. This has an even higher selectivity of H_2S to CO_2 than DMPEG and methanol. The Purisol wash can be used both at ambient temperatures and down to -15 °C. The fourth commercially used detergent is propylene carbonate in the fluorine solvent process. It is mainly used when there is no or a little H_2S in the flue gas stream. However, it is not completely soluble in water and it irreversibly reacts with water and CO_2. Due to additional thermal instability, propylene carbonate can only be heated to 65 °C and is therefore not thermally regenerable. [BEH15]

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The preferred separating method for ***post-combustion capture*** (see chapter 2.1.4) is ***chemical absorption***. Using chemical solvents, the flue gas is brought into contact with them in a first step. The carbon dioxide and the solvent enter into a chemical compound. In the next step, the solvent is regenerated and separated from the CO_2 with added heat. The regenerated solvent can then be recycled to the process. [CRE07] Essential for the technical design of the absorption process is the choice of detergent. Each detergent has different properties, relevant for the selection are the reaction rate of the CO_2 uptake, as well as the energy requirement for the desorption of the bound CO_2. Other factors influencing the correct choice of detergent are the possible loading capacity of the agent with CO_2, the selectivity, the corrosion behavior and the influence on the loss of efficiency. Different solvents require different temperatures for regeneration, which influences the efficiency. [GÖR15] The focus of research, development and application are the substance classes of alkanolamines, alkali carbonates, amino acid salts, ionic liquids and ammonia. These substances are selected because they have a higher selectivity for carbon dioxide than for nitrogen. [HER09] Currently commercially used, and therefore also best tested, is the washing with alkanolamines, the so-called *amine wash*. This washing process is already used in chemical industry processes such as ammonia production and natural gas treatment. The merging of the flue gas stream with the detergent takes place under atmospheric pressure and temperatures between 40 and 60 °C in the absorber. To regenerate the detergent, the CO_2 is dissolved in the so-called stripper at elevated temperatures between 120 and 140 °C. [KUC13; YU12] Primarily used are monoethanolamines (MEA), which have been used for many decades to separate carbon dioxide and hydrogen sulfide (H_2S). Meanwhile, more efficient amines such as diethanolamine (DEA) and methyldiethanolamine (MDEA) are in use. Also well suited are mixtures of different amines. The advantage of using amines is the fast reaction time with the carbon dioxide and the property that they have a high selectivity to CO_2 and reversibly connect to it. In addition, the relatively low price reinforces the use. Despite the low cost of procurement, the cost of upgrading the power plant increases as expensive materials need to be installed because amines can promote corrosion. It should also be noted that especially MEA volatilizes in the presence of oxygen or sulfur oxides. Therefore, a regular supply of new amines must be taken care of. [BEH15; HER09] The CO_2 can be separated with a purity of 99.9 % [HEI15]. Also used in current industrial processes is the wash with *ammonia* as a sorbent, for example, in the desulfurization of coking batches. Advantage over the amines is a higher thermal stability, and a lower corrosivity. The big disadvantage, however, is that ammonia volatilizes more quickly and is toxic, which means that extremely small leaks into the environment must be particularly strongly prevented. In comparison with MEA stands out the absorption capacity of the ammonia. To take up the same amount of CO_2, the amount of MEA triples compared to ammonia. In addition, ammonia can work just as efficiently at much lower temperatures. [BEH15; HER09] For the flue gas scrubbing with *alkali carbonates*, primarily sodium and potassium carbonate are used. The advantage of the two basic substances is the absorption enthalpy in the uptake of CO_2, which is only one third of the absorption enthalpy of MEA. The absorption enthalpy describes the released heat per kmol absorbed substance (CO_2). This reaction has the consequence that the temperature in the absorber increases less and thus the regeneration can occur with low heat input. Washing with alkali carbonates results in a limited rate of CO_2 uptake due to the rate of hydrocarbonate formation. Measures to increase the absorption kinetics are to increase the temperatures and pressures in the absorber. This can be dispensed with a further increase in temperature in the desorber. The regeneration of the solvent then takes place exclusively by lowering the pressure. This process is already suitable for synthesis gas production. Another approach to higher reaction kinetics is the addition of amines to the solvent. Mainly secondary amines are used. [BEH15; SAT12] The subject of the research is

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currently also *amino acid salts*. They are very similar in their properties to the amines, but can be neutralized by mixing with a base, which reduces the volatility, resulting in less evaporation of the process. In addition, they are less toxic than ammonia and have a high overall stability against oxidative and thermal degradation. Also part of the research, but not yet used commercially, are ionic liquids. They are similar to ionic salts, but have no crystalline lattice structure and are liquid even at low temperatures. Of great interest is the possibility to substitute the liquids with other substances in order to adapt their absorption capacities to the required conditions. [BEH15]

Carbonate looping carbon capture is a two-step dry sorption process that is also a post-combustion process. The process is based on the use of limestone. The Carbonate Looping consists of two fluidized bed reactors, the carbonator and the calciner. The carbonator is supplied with the flue gas discharged from the power plant. There, the so-called CO_2-integration takes place. Together with the lime (CaO) previously burned in the calciner, the CO_2 is burnt to calcium carbonate ($CaCO_3$). This reaction takes place at temperatures of about 650 °C. The calcium carbonate transferred from the carbonator to the calciner is further heated to about 900 °C, because at this temperature the CO_2 separates again from the lime. In order to keep the process running in the calciner, oxygen must be combined with a raw material and burned to keep the temperature at 900 °C. In addition, fresh $CaCO_3$ (make-up $CaCO_3$) must be introduced constantly from the outside, since the lime increasingly loses its capacity to absorb CO_2 after several cycles and thus increasing sintering of the pores. Due to the increase in temperature, the CO_2 dissolves from the solid and can be separated with the help of a cyclone. The almost completely pure carbon dioxide can then be further cooled and prepared for transport. The remaining lime is passed back into the carbonator, while lime that can no longer be used as well as calcium carbonate and ash are separated from the combustion process. [EPP15; KRE14; STR09] When depositing the unusable $CaCO_3$, it is possible to use the fact that calcium carbonate can easily be reused as building material and therefore no additional waste is generated. [FRA10] For the capture of CO_2, the additional combustion in the calciner increases the fuel supply of the entire power plant by a third. However, the power output of the power plant can be increased by up to 50 %, since the heat produced during combustion can first be converted into steam and then into electricity via heat recovery steam generators. Also important is the supply of pure oxygen for the combustion in the calciner, as otherwise impurities, for example by nitrogen, take place, whereby a separation of pure CO2 is no longer possible. [EPP15] Carbonate looping is still in a developmental stage and is not used commercially. The literature shows efficiency losses of 5 to 9 percentage points. The biggest losses are caused by the additional firing in the calciner, since similar to the oxyfuel process, pure oxygen is used there, which previously had to be separated in an energy-intensive way. The advantage of the process are the relatively low avoidance costs of less than € 20 per ton of CO_2. This is especially because limestone is cheap to buy worldwide. [EPP15; KRE14]

The principle of ***adsorption*** is based on the adhesion of molecules to surfaces of another substance. The connection is not chemical, but physically caused by van der Waals forces. The adsorbing substance, the adsorbent, can be both a liquid and a solid. The gas component to be adsorbed is called adsorptive. The process of separation by adsorption always consists of adsorption and desorption in order to release the absorbed substance again. [GÖR15] The larger the surface of the adsorbent, the more CO_2 can be absorbed in the case of flue gas cleaning. Therefore, particularly porous materials are well suited for use as adsorbent. Activated carbon, zeolites and other inorganic oxides, such as, for example, aluminum oxides, are preferably used. [HÜB15] The use of activated carbon is widespread because it is highly available at low cost and is both thermally

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stable and has low sensitivity to moisture. However, the adsorption of CO_2 is relatively low, which is why attempts are made to increase the capacity by modifying the surface. The focus of research is the enlargement of the surface, as well as a chemical processing of these, in order to increase the absorption capacity. The other group of substances commonly used as an adsorbent are the zeolites. Their crystalline structure and three-dimensional pores create a large surface area. The enrichment with (earth) alkali metals additionally attempts to increase the affinity of the zeolites for carbon dioxide. [YU12] The pore size of the adsorbents has an important influence on the course and success of the gas separation. If the pores are so large that the diameter is exactly between the sizes of the molecules to be separated, CO_2 and N_2, then one substance can pass through the adsorbent while the other is retained. If the pores are slightly larger than the larger of the two components to be separated, then the separation results from the different diffusion rates. Here, the larger molecule diffuses slower than the small. [BAE11] In order to increase the efficiency of adsorption, methods such as pressure swing and temperature swing adsorption are used. Pressure swing adsorption (PSA) increases the pressure of the gas to be purified. This effect causes the CO_2 to bind more strongly to the solid than the nitrogen. Once the maximum loadability of the solid has been reached, and accordingly the entire surface is wetted, the desorption step follows. The pressure is reduced again and the attached substance is released separately from the remaining components. To ensure continuous adsorption, two adsorbers must be operated in parallel. While one is in adsorption, the other is regenerated and emptied for re-uptake. Advantage of the PSA are the fast process steps between pressure increase and decrease. An alternative to pressure swing adsorption is vacuum swing adsorption. There is a regeneration pressure of less than one bar, as this is cheaper and more energy efficient than to compress the entire voluminous feed stream. [HEI18; BAE11] Alternatively, temperature swing adsorption (TSA) can be used. However, this is subject to the disadvantage that the heating and cooling processes take much longer than PSA. Convincing with the TSA, however, is the more effective cleaning of the adorber. [BAE11]

Membrane systems are another potential method of CO_2 capture that is currently being researched. With the help of a membrane, the CO_2 should be separated from the gas mixture. Main drive of the gas mixture separation are the pressure and concentration gradient of the components. In order to set an increased pressure gradient, which ensures a better flow through the membrane, the flue gas must first be densely compressed. Optionally, the pressure of the gas can be increased to 10 bar, or a vacuum on the membrane of 0.1 bar can be generated. [FRA10; MER10] Decisive for the successful separation of a substance, in this case CO_2, is the permeability of the membrane. It depends on the concentration difference, the membrane surface and the separation quality of two components. The higher the permeability of a membrane, the smaller it can be, which can reduce costs. Additionally desirable is a membrane as thin as possible, since its thickness behaves antiproportional to the gas flow. The thicker the membrane, the lower the flow. [FÖR15] Already in technical operation are membranes for the separation of hydrogen from gas mixtures, as well as the separation of CO_2 and N_2 in the natural gas treatment. In the latter method, polymer membranes are used, but their use for flue gas scrubbing is not yet mature, since the CO_2 concentrations in the exhaust gas are too low for economical use. [HÜB15] Since the energy expenditure in connection with the deposition rate and the degree of purity of the CO_2 cannot yet compete with other separation processes, no plant with this equipment is currently in operation. According to current technical knowledge, the membrane process is currently achieving a separation rate of 50 % and a comparatively low degree of purity of CO_2 of only 80 %. To compensate for these weaknesses in the future, concepts such as the return of the retentate (the

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remaining gas flow) to the feed are available. This recycling would lead to an increase in the CO_2 concentration in the feed and thus a higher separation. It is estimated that in the long term the purity can be increased up to 95 % and the deposition rate to 90 %. For the efficiency of power plants with built-in membrane technology losses of 7 to 9 percentage points are to be expected, which makes the procedure attractive. [FRA10]

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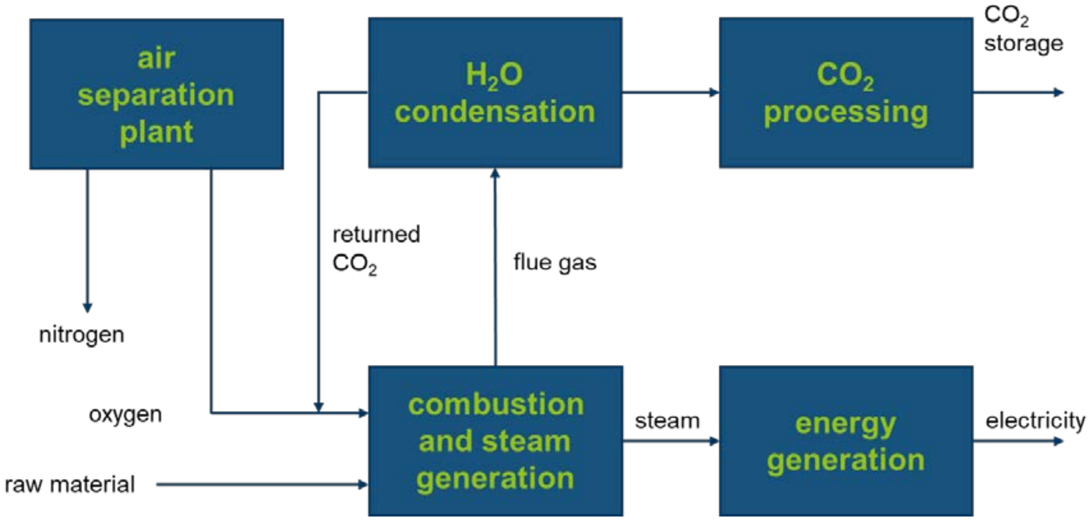
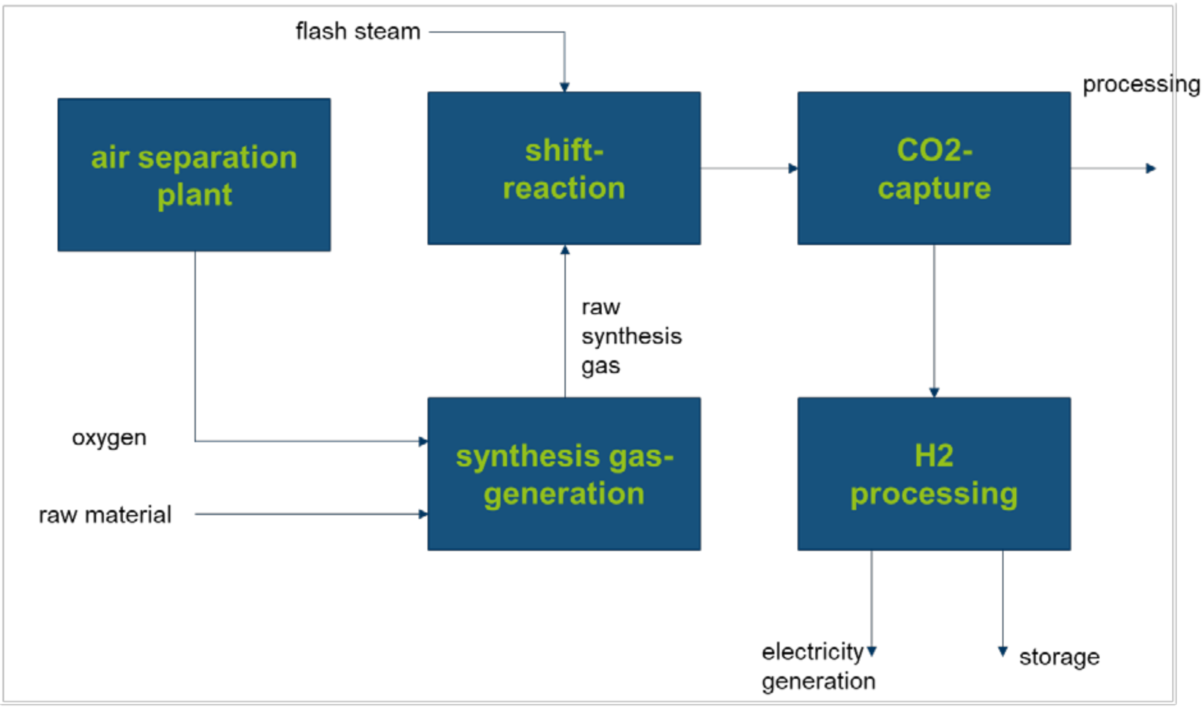
A.2 Schematics of Carbon Capture Techniques

A.2.1 Oxyfuel



A.2.2 Pre-Combustion Capture



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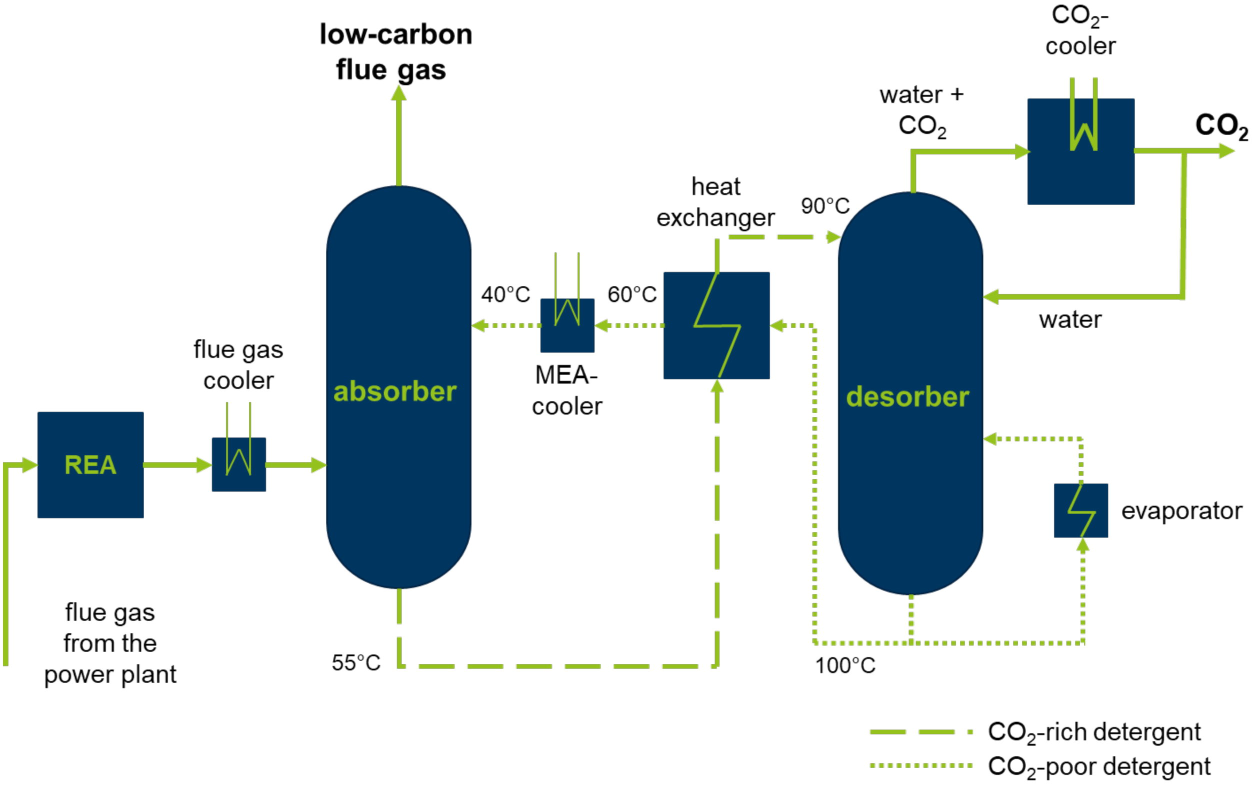
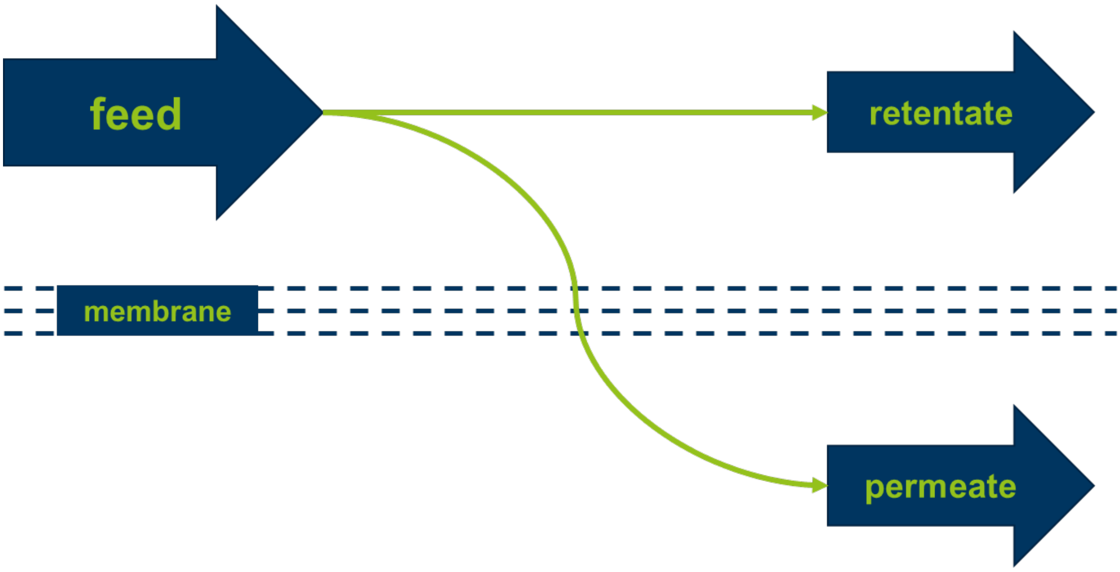
A.2.3 Post-Combustion Capture

Chemical absorption:



Membrane:



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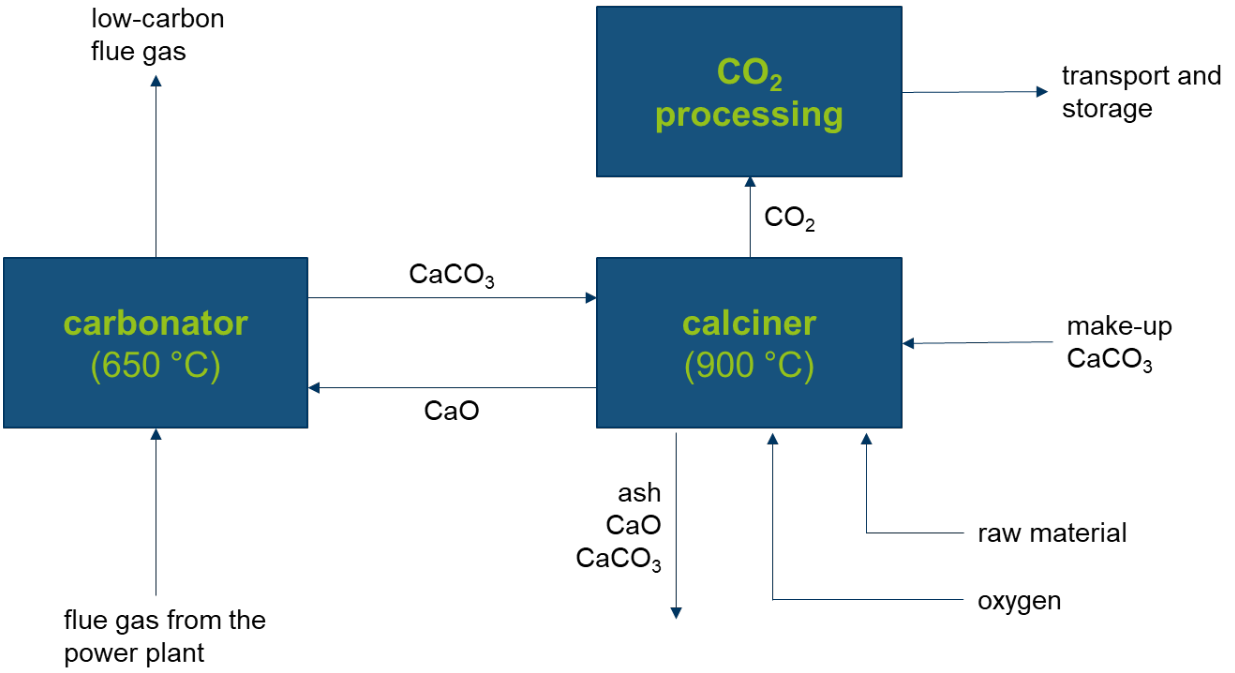
Carbonate looping:



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A.3 Evaluation and Priority Setting Matrix – Description of Assignments

The increase of the relatively low purity of 95 % of the CO_2 deposited in the oxyfuel process (1) is on the x-axis in the middle field. However, the importance for process efficiency is low. Despite the low purity, the overall process can have a degree of separation of over 90 %. The degree of purity could for example be increased by additional downstream processes and the reduction of false air intake. These measures, however, would not have a positive effect on the efficiency of the power plant due to their additional energy input, the same amount of CO_2 would be deposited with a slight better efficiency. On the other hand, the solution to the air separation plant problem (2) can have a significant impact on the power plant, as it causes the most energy losses. However, since no adequate substitute for the production of pure oxygen is used, solving the problem is technically difficult. The material modification for the high combustion temperatures (3) can be sorted into field B as well as (1). Although the conversion of the components to more heat-resistant materials is expensive, but technically feasible. Since the power plant cannot be operated safely and intact in the long term without adapting the currently used materials, a solution to the challenge means long-term stability of the power plants.

Similar to the challenge (3), the problem of the hydrogen-rich gas stream in pre-combustion power plants (4) can be classified. As the gas turbines are confronted with higher hydrogen-concentrated gases, the chromium content in the steel of the turbines must be changed. Since maximum power generation can only be achieved by optimizing the design of the turbine, this challenge is very important. The choice of carburetor (5) is well solvable due to the predictability on the basis of the process parameters. Since the most suitable gasifier gives the synthesis gas the best properties for further processing, the process can be improved. The integration of the pre-combustion process into the power plant (6) is more difficult. Due to many interfaces to be adapted on the one hand, a considerable technical effort is created, on the other hand, the risk of total failure increases in the event of a fault. Therefore, the technical feasibility is difficult to accept, whereas it is questionable whether the associated risk justifies an improvement in efficiency.

The challenges of the post-combustion process are spread over all four fields. The only challenge in the field D with high technical implementation difficulty and high relevance for the process efficiency is the regeneration effort of the detergent in amine scrubbing (7). Since 80 % of the energy used for amine scrubbing is used for regeneration, there is enormous potential for savings, which has an impact on the performance of the power plant. This contrasts with the research process that has been initiated so far for alternative detergents, none of which can be used commercially. Also technically difficult to implement is a partial pressure increase of the CO_2 (8) in the physical absorption, because the pressure in the absorber is higher than 20 bar. Since the partial pressure cannot be increased in the flue gas, the pressure difference of over 20 bar cannot be avoided. Due to the unforeseeable solution of the challenge this is not relevant for the process efficiency. Instead, the focus of the physical absorption should be placed on the pre-combustion separation, since there the gasification takes place under high pressure (30 bar). The difficulties of the membrane process are in fields A and C. The fact that multiple amounts of gas are transported through the membrane despite low CO_2 content in the exhaust gas, an increase of the membrane size (9) can hardly be prevented. Since the goal would be to downsize the membrane and increase the CO_2 concentration, which requires additional process steps, there would be no faster or better flow, and thus, beyond the cost of the membrane, there is no improvement in the process. The second challenge in membrane deposition has already been solved in practice and brings a tremendous increase in process efficiency, placing it in field A. The fact that either the

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gas stream has to be compressed or a vacuum has to be produced at the membrane (10) does mean an additional outlay, which however is technically easy to implement and by means of which the flow through the membrane can be determined. In order to replace the additional heat input at the calciner in the Carbonate Looping (11) with combustion of oxygen and thus required air separation plant, there are already approaches that are technically well implemented. However, since only 1.5 percentage points can be saved in the loss of efficiency, this is of little relevance. The simplest implementation in the individual post-combustion process is to avoid adsorber failure during adsorption (12). To ensure continuous cleaning, either an adsorber can be available in reserve or a third adsorber can be permanently integrated so that an adsorber always remains in a waiting position between adsorption and desorption.

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A.4 Hydrogen Infrastructure

A.4.1 Mixture of Hydrogen and Natural Gas

Additional tables showing the changed material properties with admixture of H_2 (natural gas Holland L North Sea H and Russian natural gas H). With an admixture of 10 % by volume, the relevant gas characteristics are within the limits of DVGW-AB G 260. [MÜL2013]

a) Erdgas Holland-L + H2

Methan	CH4	83,16	82,33	81,50	79,00	74,84	70,69	66,53	58,21	49,90	41,58
Stickstoff	N2	10,08	9,98	9,88	9,58	9,07	8,57	8,06	7,06	6,05	5,04
Kohlenstoffdioxid	CO2	1,57	1,55	1,54	1,49	1,41	1,33	1,26	1,10	0,94	0,79
Ethan	C2H6	4,04	4,00	3,96	3,84	3,64	3,43	3,23	2,83	2,42	2,02
Propan	C3H8	0,81	0,80	0,79	0,77	0,73	0,69	0,65	0,57	0,49	0,41
n-Butan	n-C4H10	0,23	0,23	0,23	0,22	0,21	0,20	0,18	0,16	0,14	0,12
n-Pentan	n-C5H12	0,06	0,06	0,06	0,06	0,05	0,05	0,05	0,04	0,04	0,03
n-Hexan	n-C6H14	0,05	0,05	0,05	0,05	0,05	0,04	0,04	0,04	0,03	0,03
Wasserstoff	**H2**		**1**	**2**	**5**	**10**	**15**	**20**	**30**	**40**	**50**
Summe		100	100	100	100	100	100	100	100	100	100
Brennwert	H_{sv} [kWh/m³]	**10,34**	**10,28**	**10,21**	**10,00**	**9,66**	**9,32**	**8,98**	**8,29**	**7,61**	**6,93**
Normdichte	ρ_n [kg/m³]	**0,834**	**0,827**	**0,819**	**0,797**	**0,759**	**0,722**	**0,685**	**0,610**	**0,536**	**0,461**
Relative Dichte	d [-]	**0,645**	**0,639**	**0,634**	**0,616**	**0,587**	**0,558**	**0,530**	**0,472**	**0,414**	**0,357**
Wobbeindex	W_s[kWh/m³]	**12,88**	**12,85**	**12,82**	**12,74**	**12,60**	**12,47**	**12,34**	**12,07**	**11,83**	**11,61**
Methanzahl	Mz [-]	**86,0**	**85,3**	**84,6**	**82,6**	**79,2**	**75,7**	**71,9**	-	-	-

b) Erdgas Nordsee-H + H2

Methan	CH4	86,25	85,39	84,53	81,94	77,63	73,31	69,00	60,38	51,75	43,13
Stickstoff	N2	0,93	0,92	0,91	0,88	0,84	0,79	0,74	0,65	0,56	0,47
Kohlenstoffdioxid	CO2	1,91	1,89	1,87	1,81	1,72	1,62	1,53	1,34	1,15	0,96
Ethan	C2H6	8,56	8,47	8,39	8,13	7,70	7,28	6,85	5,99	5,14	4,28
Propan	C3H8	1,89	1,87	1,85	1,80	1,70	1,61	1,51	1,32	1,13	0,95
n-Butan	n-C4H10	0,39	0,39	0,38	0,37	0,35	0,33	0,31	0,27	0,23	0,20
n-Pentan	n-C5H12	0,05	0,05	0,05	0,05	0,05	0,04	0,04	0,04	0,03	0,03
n-Hexan	n-C6H14	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,01	0,01	0,01
Wasserstoff	**H2**		**1**	**2**	**5**	**10**	**15**	**20**	**30**	**40**	**50**
Summe		100	100	100	100	100	100	100	100	100	100
Brennwert	H_{sv} [kWh/m³]	**11,90**	**11,82**	**11,74**	**11,48**	**11,06**	**10,64**	**10,22**	**9,38**	**8,55**	**7,71**
Relative Dichte	d [-]	**0,645**	**0,639**	**0,633**	**0,616**	**0,587**	**0,558**	**0,529**	**0,471**	**0,414**	**0,356**
Wobbeindex	W_s[kWh/m³]	**14,83**	**14,79**	**14,75**	**14,63**	**14,44**	**14,25**	**14,05**	**13,67**	**13,28**	**12,91**
Methanzahl	Mz [-]	**75,3**	**74,8**	**74,4**	**73,0**	**70,6**	**67,9**	-	-	-	-

c) Russ. Erdgas-H + H2

Methan	CH4	97,79	96,81	95,83	92,90	88,01	83,12	78,23	68,45	58,67	48,90
Stickstoff	N2	0,82	0,81	0,80	0,78	0,74	0,70	0,66	0,57	0,49	0,41
Kohlenstoffdioxid	CO2	0,09	0,09	0,09	0,09	0,08	0,08	0,07	0,06	0,05	0,05
Ethan	C2H6	0,88	0,87	0,86	0,84	0,79	0,75	0,70	0,62	0,53	0,44
Propan	C3H8	0,29	0,29	0,28	0,28	0,26	0,25	0,23	0,20	0,17	0,15
n-Butan	n-C4H10	0,1	0,10	0,10	0,10	0,09	0,09	0,08	0,07	0,06	0,05
n-Pentan	n-C5H12	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,01	0,01	0,01
n-Hexan	n-C6H14	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Wasserstoff	**H2**		**1**	**2**	**5**	**10**	**15**	**20**	**30**	**40**	**50**
Summe		100	100	100	100	100	100	100	100	100	100
Brennwert	H_{sv} [kWh/m³]	**11,12**	**11,04**	**10,97**	**10,74**	**10,36**	**9,98**	**9,60**	**8,84**	**8,08**	**7,32**
Relative Dichte	d [-]	**0,568**	**0,563**	**0,558**	**0,543**	**0,518**	**0,493**	**0,468**	**0,418**	**0,368**	**0,318**
Wobbeindex	W_s[kWh/m³]	**14,75**	**14,71**	**14,68**	**14,57**	**14,39**	**14,21**	**14,03**	**13,67**	**13,31**	**12,97**
Methanzahl	Mz [-]	**94,5**	**93,6**	**92,7**	**89,9**	**85,5**	**81,0**	-	-	-	-

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