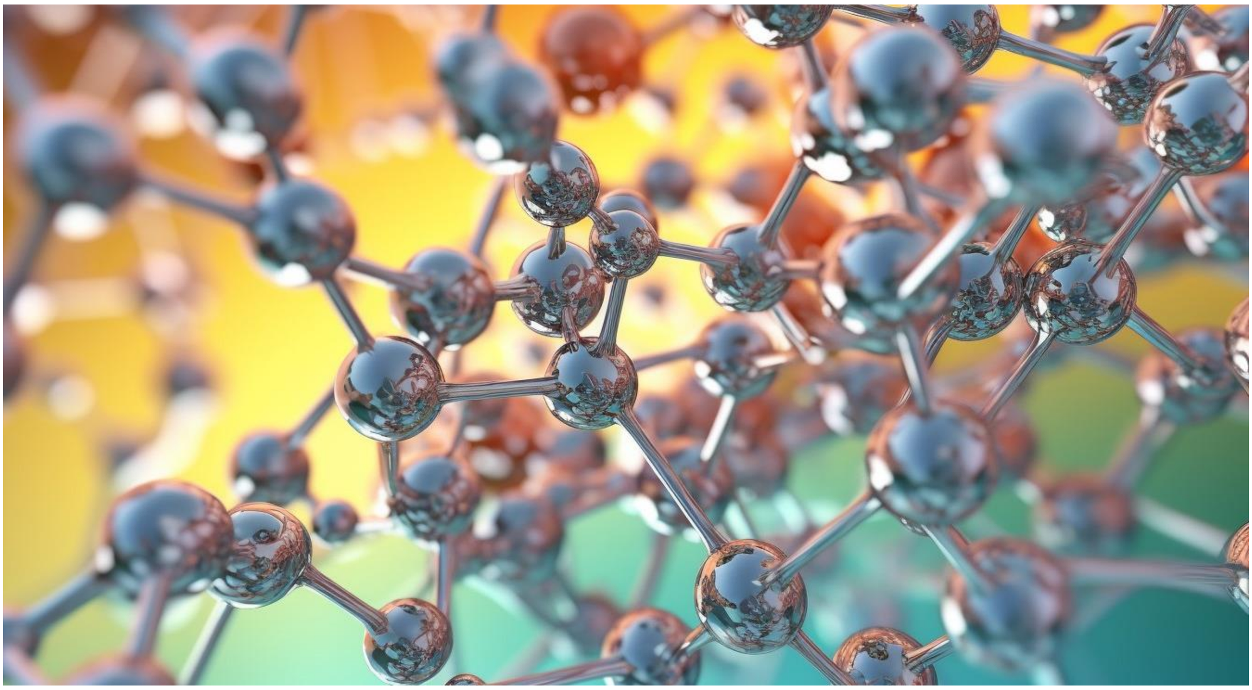
German Japanese Energy Transition Council



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Roadmaps towards a climate neutral petrochemical production system

Comparative analysis for Germany and Japan

Imprint

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METI Ministry of Economy, Trade and Industry

Table of Contents

List of Abbreviations, Units and Symbols

Abbreviations

ARA	Antwerp-Rotterdam-Amsterdam
ARRRA	Antwerp-Rotterdam-Rhine-Ruhr-Area
BAT	Best available technology
BCG	Boston Consulting Group
BDI	The Federation of German Industries
BECCU	Bioenergy with carbon capture and utilization
BMBF	German Federal Ministry of Education and Research
BMWi	German Federal Ministry for Economic Affairs and Energy
CBAM	Carbon border adjustment mechanism
CCfD	Carbon Contract for Difference
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CHP	Combined heat and power
cLCA	Carbon life cycle analysis
CNP	Carbon neutral port
DAC	Direct air capture
EU ETS	European Union Emissions Trading System
EWI	Institute of Energy Economics at the University of Cologne
Fraunhofer ISI	Fraunhofer Institute for Systems and Innovation Research
FT	Fischer-Tropsch
FY	Fiscal year
GDP	Gross domestic product
GHG	Greenhouse gas
GIO	Greenhouse Gas Inventory Office of Japan
HVC	High value chemicals
IRA	The Inflation Reduction Act of 2022
ISCC	International Sustainability and Carbon Certification
JCIA	Japan Chemical Industry Association
LCA	Life cycle analysis
LNG	Liquified natural gas
LPG	Liquefied petroleum gas
MCH	Methylcyclohexane
METI	Ministry of Economy, Trade and Industry (Japan)
MtA	Methanol-to-aromatics
MtO	Methanol-to-olefins
NEDO	New Energy and Industrial Technology Development Organization (Japan)
PAJ	The Petroleum Association of Japan
PIK	Potsdam Institute for Climate Impact
PPA	Power Purchase Agreement
PtG	Power-to-gas
PtL	Power-to-liquid
PtX	Power-to-X
PV	Photovoltaic
R&D	Research and development
S+3E	Safety plus Energy security, Economic efficiency and Environmental sustainability

SAF	Sustainable aviation fuel
SMEs	Small and medium-sized enterprises
SMR	Steam methane reforming
TU Berlin	Technical University of Berlin
UBA	German Environment Agency
VCI	German chemical industry association

Units and Symbols

$	US dollar
%	Per cent
€	Euro
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
g	Gram
H_2	Hydrogen
km^2	Square kilometer
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hour
Mt	Megatonne
MWh	Megawatt-hour
p.a.	per annum
PJ	Petajoule
t	Tonne
TWh	Terawatt-hour

List of Tables

List of Figures

Executive Summary

In order to limit global warming and fulfill their contributions to the Paris agreement, both Germany and Japan have set targets for climate neutrality towards the middle of the century. Reaching these goals will imply transformation of all sectors of society to avoid all fossil greenhouse gas emissions, heavy industry not the least. The focus of this study is the transformation of the petrochemical industry. This sector can become climate neutral but cannot be 'decarbonized', as carbon is integral to the chemical structures of the products like polymers and solvents. Reaching climate neutrality thus means that the whole lifecycle of the petrochemical products has to be regarded. Another specific challenge is today's synergetic relation of this industry to fossil transport fuel production, which cannot be maintained in a climate neutral world.

The two countries interestingly share a similar industrial structure overall, and the chemical and petrochemical industry is one of the major industries in both countries. The countries' respective chemical industries are the third and fourth largest in the world in terms of sales, but at the same time, these industries represent just over 5% of the respective countries' greenhouse gas emissions. However, these scope 1 emissions of the chemical industry itself are far less relevant than the end-of-life emissions of their products, which belong to scope 3 and are thus not counted under the chemical industry in the country greenhouse gas balances. To mediate these emissions, there is a need to set the direction, draw out paths and investigate possible alternatives for how the petrochemical industry can be become climate neutral. In this report, the existing scenario analyses, energy strategies and roadmaps dealing with this issue in the two countries are compared, as well as the current state of their petrochemical industries. We highlight similarities, differences and identify possible areas of cooperation and exchange in order to find robust paths forward for the transformation of the petrochemical industries.

In Germany, there are multiple scenario analyses and roadmaps shaping the way towards an overall net-zero greenhouse gas emissions energy system for 2045, in which strategies for the chemical industry are described in broad terms. Furthermore, the German chemical industry association has made a pathway analysis focusing specifically on the chemical industry. The strategies presented to reach net-zero emissions show a priority for defossilization of the feedstock, particularly the use of CO_2-based feedstock sources (often at least partly imported) through carbon capture and utilization (CCU) processes, and a clear shift to renewable electricity to provide the heat and steam for the chemical processes, and for renewable hydrogen production. Hydrogen is needed as an input for production using alternative feedstocks, especially CO_2. The potential role of recycled feedstock and in particular biomass is however less clear. It is also still uncertain where the CO_2 may be sourced. The German roadmaps often point to the dependence and interaction with policy and government actions for the industry and its transition, and it is argued that the business case to transform this industry is lacking. Tools and prerequisites mentioned to enable a transformation are for example Carbon Contracts for Difference (CCfDs), green lead markets, a sufficiently low electricity price (e.g., through Power Purchase Agreements), in combination with a sufficiently high CO_2 price, and a general global harmonization of climate policy.

In Japan, technologies and strategies for developing the energy system and reducing emissions are presented in strategy documents for energy saving, green growth and carbon neutrality, as well as in a roadmap for carbon recycling. Some of the technologies discussed relate to the petrochemical industry as well. Feedstock-related strategies include CCU technologies, carbon and resource recycling, and use of biomass for feedstock. Energy-related strategies include decarbonized electricity production, electrification and decarbonization of the heating system by efficient use of waste heat and conversion of waste heat to electricity and electric heating, production and use of synthetic fuels, rationalization of production processes, and adoption of best available technologies (BAT). Many strategies also require hydrogen, and CO_2 emitted from combustion to be captured and used or stored. The roadmaps encourage further R&D efforts, investments, and visions for a carbon neutral society in 2050. The uncertainty about emission reduction and cost-effectiveness of new production processes, however, is identified to be a main challenge making companies hesitant to invest. Additionally, strategies must be adapted to fit the island nation of Japan, where the energy self-sufficiency is low and energy can only be produced domestically or imported by ship.

The two countries share characteristics such as a large petrochemical industry facing strong global competition and high energy prices. Both countries also have energy systems highly dependent on imported energy. Today, these imports relevant for petrochemicals are largely fossil in the form of oil and natural gas for Germany, and oil and coal for Japan. Finding alternative non-fossil energy markets is therefore an important issue, where both countries would strongly benefit from a global market for green chemical energy carriers and feedstock, such as naphtha, methanol, hydrogen, or ammonia.

In other ways, the countries and their industries are very different and strategies will also have to be adapted to the national conditions. One major difference is how the countries are imbedded in the global and regional energy systems, which has a direct effect on the petrochemical industry as it requires large amounts of energy resources, for feedstock as well as for energy uses. Germany can exchange electricity and fuels with neighboring countries through grids, pipelines and land transport, whereas Japan is limited to overseas transport. The opportunities are thus also different for electrification strategies and diversification of the energy supply. The surrounding policy framework also differs, which is reflected in how the roadmaps are framed and how policy recommendations are presented.

The similarities and differences shape what kinds of cooperation between the two countries may be especially fruitful. There are opportunities to learn from each other in technology and policy development, for example, as a country with geographically restricted access to other countries and resources, Japan has extensive experience when it comes to resource and energy efficiency, whereas Germany, through its Energiewende, has a long history of developing long-term strategies and policy for transformation of energy systems. There are also benefits to cooperate when it comes to the development and market introduction of new production processes and systems, including gathering experience with their practical implementation to reduce economic uncertainty. Especially, both countries have identified capture, processing and use of CO_2 in petrochemical products as an important strategy for defossilizing the petrochemical industry, and could collaborate in its development. Opportunities for collaboration on the global arena include joint strategies for approaching potential trade partners to build partnerships or even a global market for non-fossil energy carriers and chemical feedstocks. The latter may include the development a harmonized global policy approach, for example aligning standards and requirements to build markets for green products and production processes.

For both country's industries, the vision of a climate neutral production system and pathways to reach it are yet unclear in many aspects, and as it seems even more so for the petrochemical industry than for other energy intensive industries. Cooperating can help alleviate uncertainties, enable spread of new technologies and new industrial systems, provide opportunities to learn from each other's experiences, and find robust ways forward. This can also help speed up the transition, something that is essential in this challenge where time is very much of the essence to limit the negative impact on our planet's climate.

1 Introduction

Germany and Japan have a great deal in common. The land areas of Germany and Japan are approximately 350,000 km^2 and 370,000 km^2, respectively (Federal Foreign Office of Germany, n.d.; MOFA, n.d.). Nominal gross domestic product (GDP) is also very close (in 2021), with both Germany and Japan at about US$4-5 trillion (Trading Economics, 2023b, 2023a). Another common point is that both the Germans and the Japanese have achieved an impressive recovery from the post-war economic crisis. In terms of population however, Germany's is only about 60% that of Japan, and although both countries share the social challenge of decreasing population, a comparison of GDP per capita shows that Germany's is about 30% higher than that of Japan at currency exchange rates (Statistics Bureau, 2022; Statistisches Bundesamt (Destatis), n.d.).

Interestingly, the two countries also have very similar industrial structures. For example, both have a total of over 3.5 million companies, more than 90% of which are small and medium-sized enterprises (SMEs) (JETRO, 2021; SME Support Japan, n.d.). And the manufacturing industry accounts for more than 20% of GDP in both countries (METI, 2019). Both countries are also known for their automobile and machinery industries, which are key national industries in both Germany and Japan and important customers for the petrochemical industry, as they unfold demand for products such as special engineering plastics like polycarbonate and polyamide or polyurethane foams, as well as coatings. The chemical industry is an important part of both countries' industrial systems, alongside the other CO_2 intensive industries steel and cement. The petrochemical industry is the most significant part of the chemical sector, being the main contributor both to the sector's economic value and to its emissions. Through complex chains of production processes, the petrochemical industry transforms hydrocarbon resources, particularly oil, into basic and specialty chemicals, particularly polymers.

With this background, the petrochemical industry is indispensable in terms of economy and employment for both countries and has developed significantly as a key industry in the world. Hence, as various initiatives are carried out to achieve a climate neutral society in the future, efforts to reduce CO_2 emissions in this sector play a very important role in achieving the policy goals of both countries. However, the emissions of the petrochemical industry itself (scope 1 and 2) are far less relevant than the end-of-life emissions of their products, which belong to scope 3 and are thus not necessarily totally counted in the countries' greenhouse gas (GHG) accounts, as both countries are net exporters of raw polymers and products made of them (cars, machinery). On the other hand, petrochemical products may bind CO_2 from the atmosphere, representing a durable carbon sink, if the carbon in the waste can be recycled.

This paper therefore reviews the transformational challenge of the petrochemical industry in both Germany and Japan. Specifically, we review the social and geographical positioning and characteristics of the petrochemical industries in both countries (Chapter 2), and the status of scenarios and roadmaps in this area for achieving climate neutrality targets (Chapter 3). In the third step, based on the results of the analysis of the review of the petrochemical industry in both countries, the characteristics of the two countries are compared and discussed (Chapter 4). In the concluding part, we focus on the research areas that Germany and Japan should prioritize in cooperation and give joint recommendations for developing and introducing climate neutral solutions.

2 Industrial context

Although this study focuses on the *petro*chemical industry, it is part of the chemical industry overall, and many data are only available for the chemical sector as a whole. Therefore, data in this chapter often refer to the chemical industry, while we tried to provide as much information as possible specific to the petrochemical subsector.

2.1 Germany

The chemical industry as a whole is one of the largest industries in Germany. With 350,000 people employed (VCI, 2022b), it produces a wide range of chemicals across all segments, including basic inorganics, petrochemicals, polymers, agrochemicals, specialties and cosmetics (Cefic, 2022a). Also globally, the German industry is one of the top players, especially as an exporter of chemical products. Indeed, among the world's chemical industries, the German is the third largest exporter and takes the fourth place in terms of sales, after China, USA and Japan (VCI, 2022a). The country is also host to the headquarters of several of the world's largest chemical companies, including BASF, Evonik Industries as well as Lanxess and Covestro, which used to be part of the Bayer conglomerate and became independent companies in 2004 and 2015. At the same time, the industry has a large responsibility when it comes to its climate impact. In 2020, the chemical and pharmaceutical industry emitted 38.9 Mt CO_2-eq in direct emissions (VCI, 2022b), making up 5.3% of the Germany's total greenhouse gas emissions (UBA, 2022). Germany has set up the target of climate neutrality by 2045, and thus the industry faces a large challenge to mitigate these emissions and transform the industry.

2.1.1 Historical development

The structure of the German chemical industry has historical roots, some dating back as early as the 18th century. That was when the country's first fragrance producers settled in the Rhine region, and a chemical industry was then gradually built up in the region during the following century, making use of the local coal resources and by-products of coke production. Other clusters were also formed successively throughout Germany over the 19th and 20th century, in locations beneficial at the time. This can be for example close to coal resources, adjacent to other industries and in places with good connections to ports or land transport, and pipelines for energy and resources. Today, the industry can be said to be largely concentrated to six industrial clusters: Emscher-Lippe, Rheinland and Ludwigshafen along the Rhine River in the West, the North Sea (Nordsee), the Middle German Chemical Triangle (Mitteldeutsches Chemiedreieck) in the East, and the Bavarian cluster (Bayerisches Chemiedreieck) in the Southeast (see Figure 2-1). Of the German clusters, Rheinland is the largest while the Bavarian and North Sea are comparatively small. The clusters have different characteristics, both with regards to what they produce, but also in terms of infrastructure connections and resource access, and thus dependencies.

2.1.2 German chemical industry today

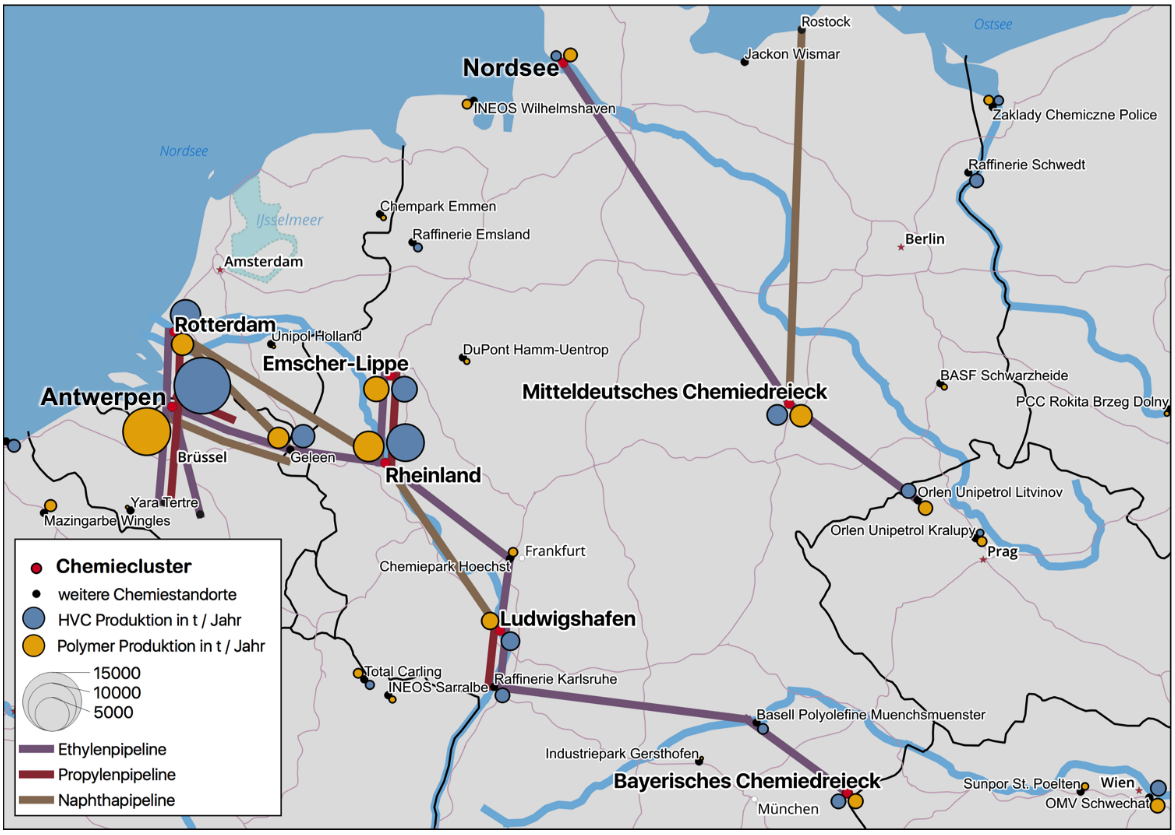

Figure 2-1: Petrochemical clusters in Germany and the Antwerp-Rotterdam-Amsterdam port area (ARA)
Source: (Scholz et al., 2023)

The German chemical industries have developed massively since their formation, not the least experiencing strong growth after World War II with the transformation from a coal- to an oil-based industry, and then later facing challenges as competition grew. It has thereby also become integrated in and dependent on the overall infrastructure and market system that it is now a part of. An example of this integration are the clusters Rheinland and Emscher-Lippe, which together with Antwerp in Belgium and Rotterdam in the Netherlands make up the superregional petrochemical cluster ARRRA (Antwerp-Rotterdam-Rhine-Ruhr-Area), integrated via oil (naphtha) and ethylene pipelines.

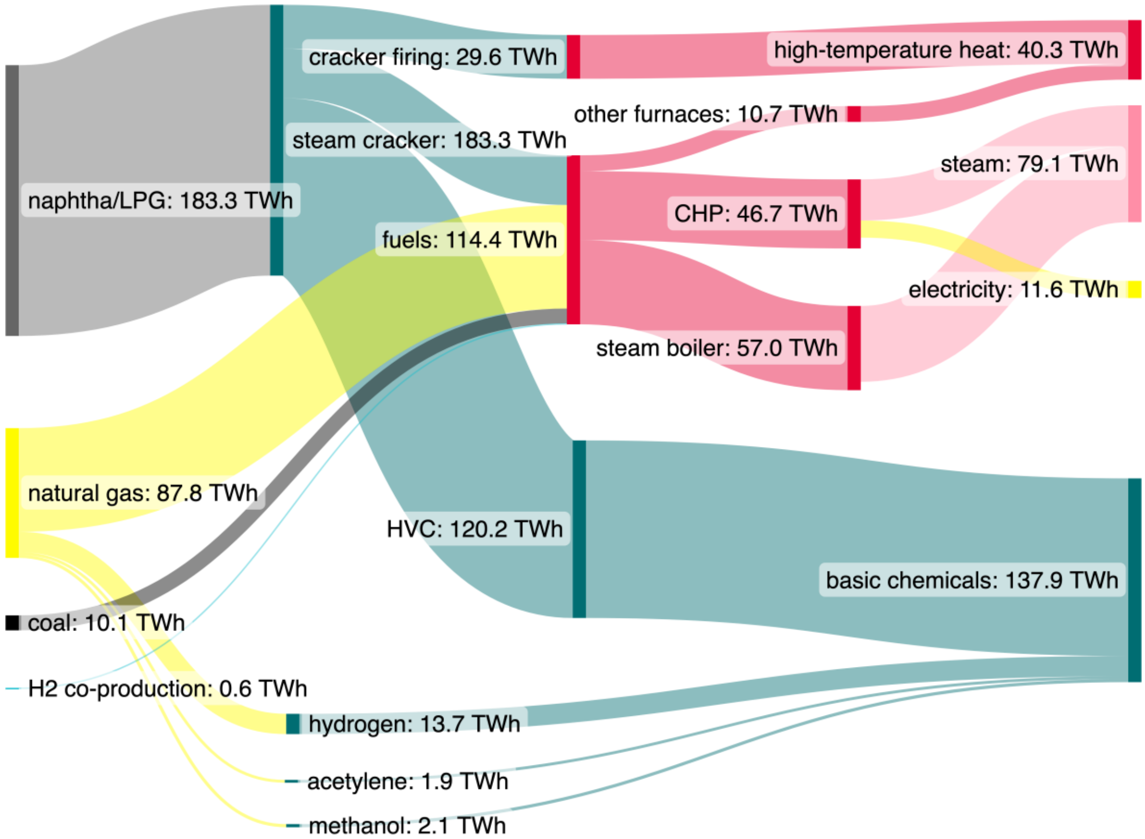

Figure 2-2: Sankey diagram for hydrocarbon energy flows in the German chemical industry
Abbreviations: LPG: Liquefied petroleum gas, CHP: Combined heat and power, HVC: High value chemicals. Source: model calculations of the Wuppertal Institute, (Scholz et al., 2023)

Most of the clusters are also strongly integrated into the gas infrastructure and are dependent on the access to natural gas. As can be seen in Figure 2-2, natural gas is the main fuel used when generating steam, heat and power for processes. Naphtha is processed in steam crackers to produce high value chemicals (HVC), although by-products from the cracking process (mainly methane, hydrogen gas and heavy oil-products) is also used for fuel and heat. While the oil-derivates naphtha and liquefied petroleum gas (LPG) clearly dominate primary energy supply, natural gas makes up 70% in BASF's Ludwigshafen site (Scholz et al., 2023). On the other hand, in the Rheinland and Bavarian cluster naphtha is the completely dominant energy carrier (> 90%). Dependencies also arise due to the structures within the cluster. For example, the plants in Emscher-Lippe and In Bavaria are very dependent on their respective refineries, and in the latter case the refinery does not even produce gasoline at all and instead provides more of the naphtha for the chemical industry. The various sizes of the clusters also affect their characteristics. Indeed, there is a large variation in sizes among the German clusters where the largest cluster Rheinland for example has an energy use ten times larger than the smallest cluster North Sea. The various integrations of the chemical clusters into the overall energy system, trade connections and structures mean that the different clusters have different challenges and opportunities when it comes to transforming them into climate neutral production.

2.1.3 Sustainability Agenda

Sustainability is high on the agenda in Germany, and the country has set a target to reach climate neutrality by 2045 for the country as a whole in its Climate Change Act (Klimaschutzgesetz), with intermediate sector targets for each year until 2030, and an overall intermediate target for 2040. The chemical industry in Germany has also set the target to reach greenhouse gas neutrality by 2050 (Cefic, 2022a).

The required investments that would be needed to reach the targets in the sector would be very large and long-term, and require economic viability. This is especially important for an export dependent industry such as the German, which faces strong competition on a global market. The future is however very uncertain, the higher price and lower availability of renewable electricity and energy carriers derived from it is still a hinderance, and framework conditions are still not where they need to be to fully enable an industrial transition in line with the targets. It is also unclear how the existing structures and dependencies affect the opportunities and challenges for transition. Can for example existing trade connections, cooperation structures and pipeline networks be used for leverage and help make the transition possible, or do they create an inertia that makes the challenge all the more daunting? (Janipour et al., 2022)

In any case, efforts towards more environmentally sustainable production are currently being made in several of the clusters and the companies, and some examples are summarized below. The focus of these efforts is on chemical recycling and bio-based drop-in feedstock:

- In Ludwigshafen, there is an ongoing pilot project for chemical recycling via pyrolysis, and an upcoming partnership has been announced to deliver 16,000 t of pyrolysis oil based on mixed post-consumer waste per year to Ludwigshafen (BASF, 2019). Furthermore, smaller quantities of bio-naphtha and bio-methane are used, which are typically blended in with fossil raw materials as a drop-in solution (BASF, n.d.). Also, an electric steam cracker oven line is planned to be constructed as a demonstration plant at the BASF site in 2023 (BASF, 2022).
- The Rhineland cluster experiments with chemical recycling and production of biobased chemicals too. Pyrolysis oil is planned to be produced in the Netherlands by 2023, using in the scale of 30 t plastic waste (CHEMIE TECHNIK, 2021). Some of the oil will then be transported and processed in the steam crackers in the Rhineland. Furthermore, Covestro is operating a pilot plant to chemically recycle polyurethane from used mattresses via chemolysis (Covestro, 2023). Covestro and LyondellBasell are also partly using bio-sourced hydrocarbons for the production of polycarbonate respectively polyethylene and polypropylene (Covestro, 2020; Packaging Journal, 2019).
- In the Middle German Chemical Triangle, a bio-refinery is currently being built in Leuna, which will be able to produce chemicals from hardwood (UPM Biochemicals, n.d.). A pilot plant for chemical recycling of PET is also planned (Equipolymers, n.d.; RITTEC Umwelttechnik, 2022), and under construction is the largest PEM electrolysis plant in the world for the production of hydrogen, as well as a hydrogen pipeline (Landesportal Sachsen-Anhalt, 2022).
- In the Bavarian cluster, strategies are being set for relying more on sustainable polyolefins, where the plan is to produce 350 kt yearly by 2025 using recycled polyolefins, and 2,000 kt per year by 2030 in total from recycled and bio-based solutions (OMV, 2022a). Bio-based ethylene

was produced in the steam cracker in 2021 for the first time, and collaborations are being established for chemical recycling (OMV, 2021, 2022b).

These ongoing and planned projects are however notably still just at the beginning and are yet very small scale compared to the conventional industry.

2.2 Japan

In Japan, the chemical industry has approximately 20,000 offices, 950,000 employees, and approximately 46 trillion yen in product shipments, which accounts for more than 10% of the total manufacturing industry (METI, 2021d). It is an important industry that supports Japan's economy and employment.

CO_2 emissions in FY2019 in Japan were approximately 1 billion tons (GIO, 2023). This amount represents about 3% of the world's total CO_2 emissions. Of this amount, the industrial sector accounts for more than 35% of Japan's total CO_2 emissions (about 380 million tons), and about 15% of the industrial sector's CO_2 emissions (about 56 million tons, or 5.4 % of the country's total CO_2 emissions) come from the chemical industry. It should be noted that the chemical industry emits not only CO_2 from energy sources (electricity, heat, steam, etc.), but also emits from the use of raw materials such as naphtha. Japan aims to achieve a carbon neutral society by 2050. Therefore, CO_2 emissions from the chemical industry cannot be ignored in achieving this goal, and its reduction is an urgent issue that requires a major social reform of the entire energy system.

Japan is an island nation surrounded by the sea and is not rich in underground resources. In the past, Japan also mined coal, but as imports of cheap energy resources from overseas have expanded, the supply of domestic energy resources has gradually shrunk, and is now almost non-existent. Not many reserves of natural gas or oil have been identified. In addition, with the rapid economic growth of the 1970s, energy consumption has increased rapidly. Today, Japan relies almost entirely on imports of energy resources from overseas.

For this reason, high-density energy needed to be imported to Japan in a highly efficient manner, and more than 50 years ago Japan became the first country in the world to successfully implement a project to liquefy and transport natural gas. It has been almost 55 years since a 30,000-ton liquified natural gas (LNG) carrier from Alaska arrived in Japan in 1969. Marine transportation of natural gas by liquefied natural gas has now become a global standard.

Japan's energy self-sufficiency rate is about 12% (METI, 2022). This figure is significantly lower than that of other developed countries and is about 1/3 of Germany's self-sufficiency rate (about 35%). Japan's reliance on imports for energy resources is the reason why the Japanese chemical industry is concentrated along the coast and around ports. Figure 2-3 shows geographical locations of petrochemical complexes in Japan.

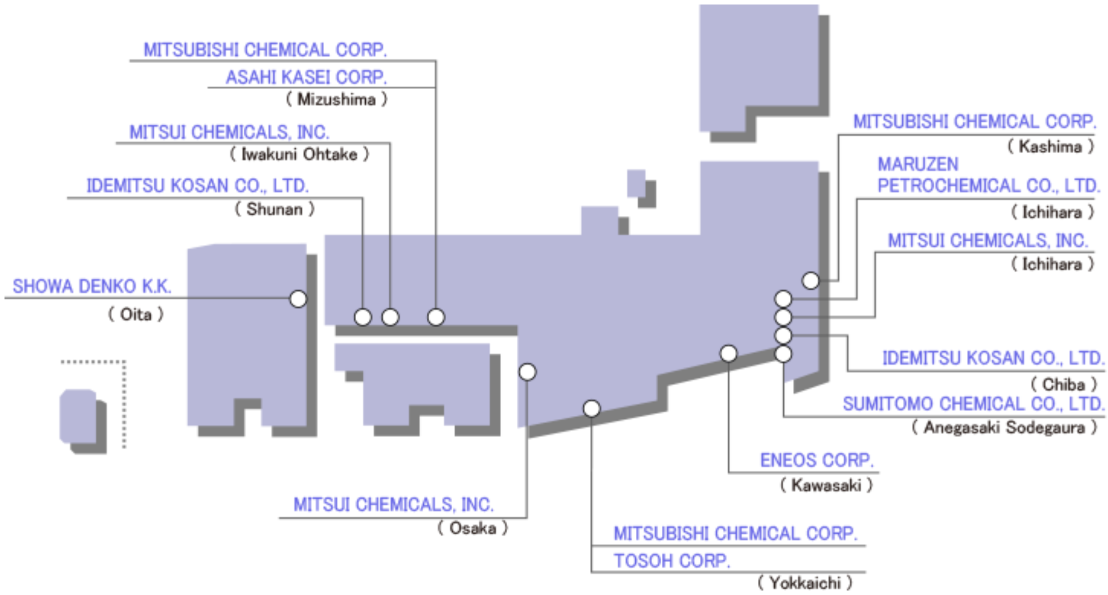

Figure 2-3: Geographical locations of petrochemical complexes in Japan
Source: (JPCA, n.d.)

Japan's first petrochemical complexes were built in Iwakuni and Ehime in 1958 to produce ethylene and polyethylene domestically. Since then, the petrochemical complexes have been efficiently producing petroleum, chemicals, electric power, and other diverse products in cooperation with each other by sharing facilities and other means with other industries.

Most of Japan's petrochemical companies are located in waterfront areas because of the convenience of shipping raw materials in and out of the country and the easy availability of land for land reclamation. On the other hand, the petroleum refining, chemical, steel, and power generation industries that make up the complex are also major emitters of greenhouse gases. Fuel such as green hydrogen, blue hydrogen, green ammonia, and blue ammonia, which are promising for decarbonization, are expected to be imported mainly from overseas. Therefore, considering the storage and utilization of these fuels after importation, the location of the waterfront area will continue to be very important for implementing collaboration among companies at the port. As a result, studies are underway for the formation of a carbon neutral port (CNP) that will significantly reduce greenhouse gas emissions in the future by developing the ability to import large quantities of hydrogen and ammonia in a stable and inexpensive manner.

Japan relies almost entirely on imports of primary energy from overseas, amounting to about 17,000 PJ of energy as shown in Figure 2-4. Fossil resources and fossil fuels (oil, coal, and natural gas) account for about 90% of primary energy, which is a source of CO_2 emissions. Of this primary energy, about 7,300 PJ (about 43%) is consumed in power generation, of which fossil fuels account for about 80% (about 5% oil, 37% coal, and 37% natural gas). From the approximately 7,300 PJ of energy, about 3,300 PJ is supplied as electricity to the industrial, transportation, and consumer sectors. The other 9,700 PJ of energy not used for power generation is consumed as raw materials and fuels in the industrial, transportation, and consumer sectors. The energy consumed in the industrial sector is about 3,146 PJ, accounting for about 18% of primary energy.

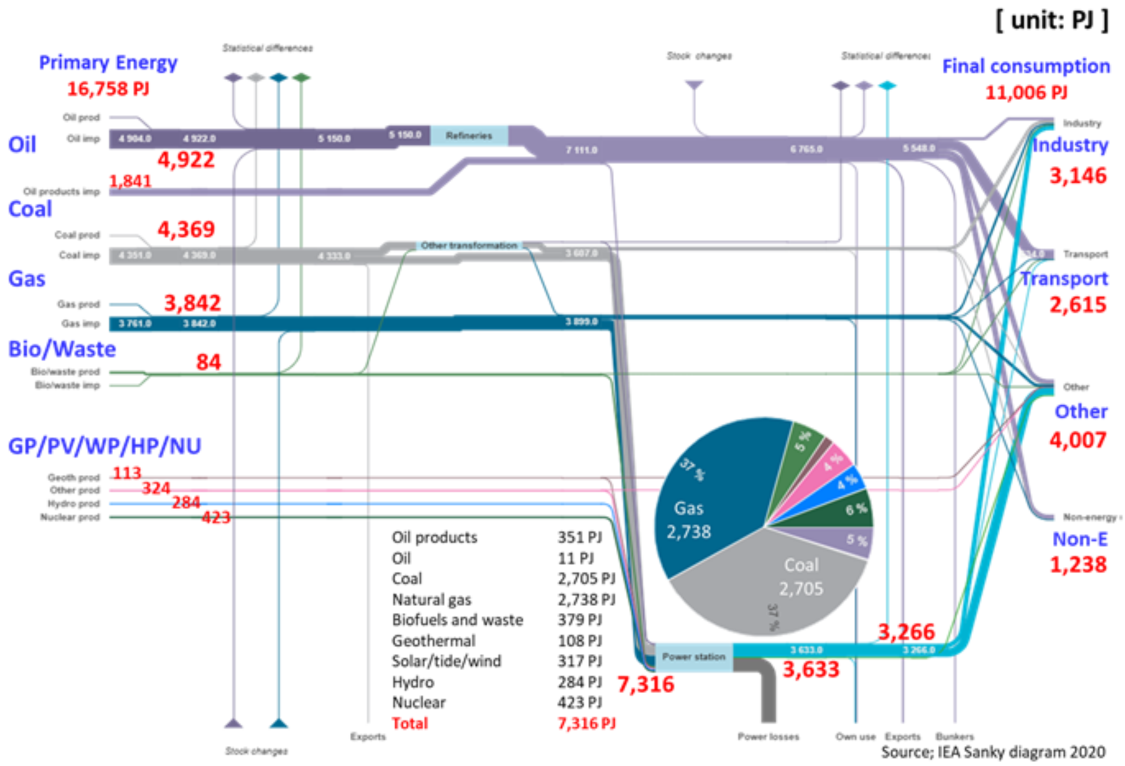

Figure 2-4: Energy consumption in Japan
Source: (IEA, 2020)

Furthermore, about 747 PJ of energy is consumed in the chemical and petrochemical sector in the industrial sector as shown in Figure 2-5. Energy consumption in the chemical and petrochemical sector consists of about 45% oil, 17% coal, 11% natural gas, and 26% electricity. As you have probably figured out by now, even if all the electricity consumed in the chemical and petrochemical sector were covered by renewable energy, it would only amount to about 26% (about 191 PJ) of the total.

The remaining energy comes from fossil fuels, and unless we recognize this and take some measures, we will not be able to achieve a fundamental reduction in CO_2 emissions. In other words, energy equivalent to the consumption of oil, coal, and natural gas must be replaced by CO_2-free raw materials and fuels.

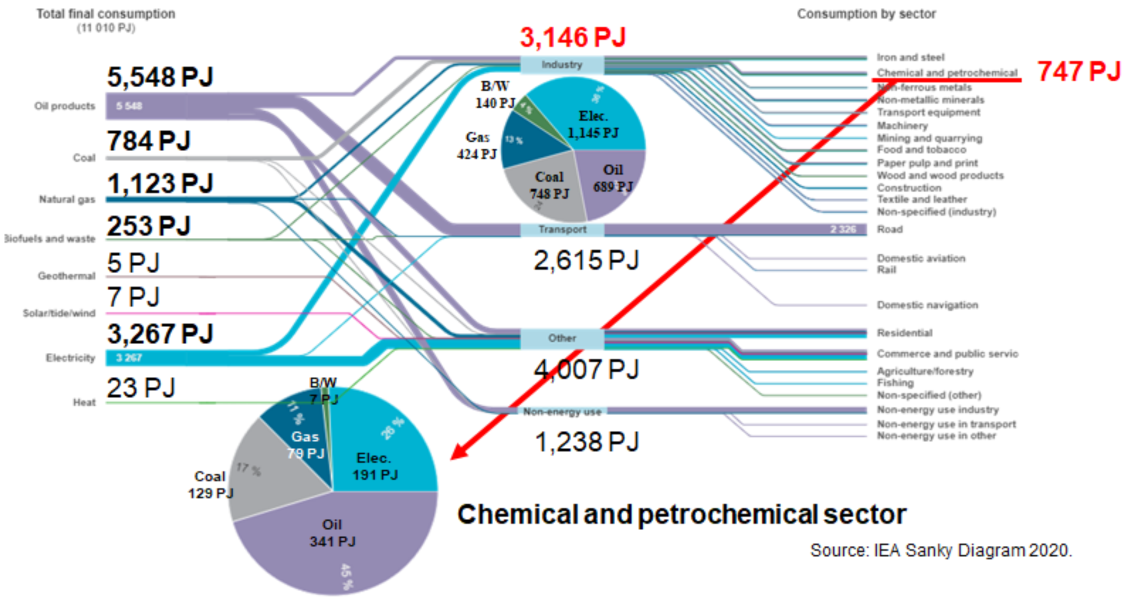

Figure 2-5: Energy consumption in the Japanese chemical and petrochemical sectors
Source: (IEA, 2020)

3 Scenarios and roadmaps for reducing emissions in the chemical industry in Germany and Japan

What are potential pathways and roadmaps for achieving climate neutrality targets by 2045/50 in Germany and Japan? This chapter analyses the current knowledge regarding this question on the basis of available long-term scenario studies for both countries, following a similar structure of aspects. Again, although the primary focus of this study is the *petro*chemical industry, most scenario studies present data for the chemical sector as a whole, and thus data in this chapter often refer to the chemical industry. Even so, the discussion and strategies described here and in the studies and roadmaps are mainly centered on the petrochemical part as this is the largest part of the chemical industry and the most challenging to transform.

3.1 Study selection criteria

With the goal of capturing the currently ongoing debate among major stakeholders in the respective countries, the following criteria were set up for the selection of studies to include:

- National focus: Focused on Germany and Japan respectively.
- Sectoral focus: Covering the chemical or petrochemical industry in terms of energy and feedstock. Studies may have a broader industrial scope, but should contain sections addressing the chemical industry specifically. Furthermore, studies with a focus on steam generation at chemical or petrochemical parks are considered relevant as well.
- Major stakeholder involvement: Commissioned by trade associations, trade unions or government agencies/ministries.
- Recent: Published earliest 2018

Thus, for example studies with a wider geographical scope (such as Global or European), too limited or too unspecific sectoral scope (e.g., focusing on ammonia only or aggregating all of industry), purely academic studies and older studies were not selected. Based on these criteria, six studies for Germany and five studies for Japan were chosen, as presented in **Error! Reference source not found.** and 3-2, respectively.

Table 3-1: The selected studies for Germany

Code	Title	Made by	Commissioner	Year
RoadChem	Roadmap Chemie 2050 Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland	Dechema and FutureCamp	VCI	2019
Wege	Wege in eine ressourcenschonende Treibhausgasneutralität	UBA	-	2019
DenaLeit	dena-Leitstudie – Aufbruch Klimaneutralität	EWI	dena	2021
KlimaPfade	KLIMAPFADE 2.0 Ein Wirtschaftsprogramm für Klima und Zukunft	BCG	BDI	2021
Langfrist	Langfristszenarien für die Transformation des Energiesystems in Deutschland 3	Consentec, Fraunhofer ISI, ifeu, TU Berlin	BMWi	2021
DeAufWeg	Deutschland auf dem Weg zur Klimaneutralität 2045 Szenarien und Pfade im Modellvergleich	Kopernikus-Projekt Ariadne and Potsdam-Institut für Klimafolgenforschung (PIK)	BMBF	2021

Table 3-2 : The selected studies for Japan

Title	Made by	Year
Energy Saving Technology Strategy	METI and NEDO	2019
The Sixth Basic Energy Plan and Long-Term Energy Supply and Demand Outlook	METI	2021
Roadmap for Carbon Recycling Technologies	METI	2021
Green Growth Strategies Associated with 2050 Carbon Neutrality	METI	2021
Keidanren Carbon Neutrality Action Plan -- Vision toward Carbon Neutrality by 2050 and Fiscal 2021 Follow-up Results (Performance in Fiscal 2020) --	Keidanren (Japan Business Federation)	2022

3.2 Germany

3.2.1 Analysis of roadmaps

The six chosen roadmaps for Germany are here presented in short, including who made or commissioned the roadmap, the type of study, ambition level and the role of the chemical sector in the roadmap. They are then summarized and compared in terms of (i) strategies and technologies to reduce emissions, both with regards to feedstock and energy, (ii) timeline for the emission reduction and strategies, and (iii) major challenges identified and policy recommendations.

3.2.1.1 Overview of roadmaps

In Germany, several documents with modelled scenarios have been developed for the energy system as a whole. These are often commissioned by government agencies including those concerned with energy, economic affairs, education, and environment. Apart from these, a similar report has been published by the Federation of German Industries (BDI). All of these take a broad approach to drawing out possible pathways for Germany to become carbon neutral by 2045, concerning all major sectors. In them, the chemical industry is considered as a part of the industry sector, for which some specific results are also presented. In contrast to this, the German chemical industry's business association has developed a roadmap specifically focused on the chemical industry. For the assessment of the German discussion on chemical industry defossilization, all these documents have been included, and a brief presentation of each is given below.

Roadmap Chemie 2050 Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland (Roland Geres et al., 2019)

The roadmap written for the German chemical industry association (VCI) investigates a possible path for transformation, measures, technologies and investments needed, and how far towards carbon neutrality the industry can progress. As such, it hopes to provide a structure to discussions from a technical perspective, to enable conclusions and focus points. Two pathways with different ambition levels are modelled, as well as a reference pathway. The first pathway named "Technology pathway", reaches 61% emission reduction from the sector by 2050 compared to 2020, while the second named "Greenhouse gas neutrality pathway" reaches 97% emission reduction. Unlike the other documents, this roadmap focuses solely on the chemical sector.

Wege in eine ressourcenschonende Treibhausgasneutralität (Purr et al., 2019)

This study, made by and for the German Federal Environment Agency (UBA), has a specific focus on resource conservation in addition to emission reduction. Six scenarios until 2050 have been produced: GreenEe1, GreenEe2, GreenLate, GreenMe, GreenLife, and GreenSupreme, describing a Germany with at least 95% reduction of emissions by 2050 compared to 1990. In line with the focus on resource conservation, the analysis considers lifestyle changes, and the scenarios avoid carbon capture and storage (CCS) and limit the use of biomass. It discusses effects in terms of greenhouse gas emissions, raw material consumption and global effects. In addition to the sectors covered also in the other reports (i.e., energy supply, building, mobility, and industry) this report also includes chapters on the waste and waste water sectors as well as agriculture and land use. Similarly to the previously described reports, the chemical industry is modelled and discussed in broad terms as a section of industry, as one of nine other industries.

dena-Leitstudie – Aufbruch Klimaneutralität (Deutsche Energie-Agentur GmbH (Hrsg.), 2021)

The German Energy Agency (dena) presents one scenario for carbon neutrality (KN100) by 2045 for the German overall system in this document, with a focus on energy sources and their required quantities. It describes an integrated energy system and society, with more detailed analysis of the building, industry, transport, and energy sectors. Furthermore, the report explores aspects like market design, innovation, societal anchoring, and the international interplay. For each chapter, central recommendations for action are presented for the coming legislative period. The chemical industry is modelled as part of the industry, and is discussed in broad terms.

KLIMAPFADE 2.0 Ein Wirtschaftsprogramm für Klima und Zukunft (BCG, 2021)

Since the first version named Klimapfade für Deutschland was made in 2018, the German government updated and tightened its climate targets. In this second version of the climate path, these updates have been taken into account. Commissioned by the federation of German industries (BDI), the study aims to formulate climate policy instruments that enable all sectors to reach the set targets for 2030 and greenhouse gas neutrality by 2045. In it, one path to climate neutrality for Germany is modelled and explored with regards to industry, transport, energy supply, and buildings, and for each of these, recommendations for policy instruments are given. The study also discusses investments and costs as well as policy issues in greater detail. For the industry sector, the basic chemical industry is one of the three parts particularly considered, alongside steel and building materials.

Langfristszenarien für die Transformation des Energiesystems in Deutschland 3 (Fleiter et al., 2021)

In this project, a future greenhouse gas neutral system by 2050 has been modelled on behalf of the German Federal Ministry for Economic Affairs and Energy (BMWi). Rather than showing one main scenario, it investigates and compares three future scenarios relying with priority on one energy source each: electricity, hydrogen and power-to-gas/power-to-liquid (PtG/PtL) respectively. Thus, advantages and disadvantages of the different paths are made clearer, and path dependencies respectively robust developments are identified. In the project, different parts of the energy system are reported in different modules, one of which is the industry sector. In the industry module, basic chemistry, iron and steel, as well as the cement and lime sector are modelled. The system has also been modelled with a particularly high regional granularity, allowing for analysis of regional differences and the varying effects and on regions with different characteristics.

Deutschland auf dem Weg zur Klimaneutralität 2045 Szenarien und Pfade im Modellvergleich (Kopernikus-Projekt Ariadne, 2021)

Made with support of the German Federal Ministry of Education and Research (BMBF), this project integrates six overall system and sector models to build scenarios for Germany's transition path to climate neutrality by 2045. In total, six scenarios are modelled for the whole system: Electrification (domestic), Electrification (import), Hydrogen (domestic), Hydrogen (import), E-fuels as well as a final Technology mix. The report presents sections for industry, transport, buildings, and energy supply. Additionally, the role of hydrogen and e-fuels is also elaborated on, as well as sector interactions and sector coupling. Policy recommendations are also given for each section. The chemical industry is briefly discussed, but no quantitative results are presented. However, the model used for the industry sector is the same as in the Langfristszenarien report described above.

Company initiatives

The roadmaps described above do not necessarily reflect planned efforts by chemical companies on the ground, where indeed several companies active in Germany have also set up targets to reach net-zero emissions by 2050. This includes BASF, Dow, Sabic, Ineos, LyondellBasell Industries, DuPont and more recently Covestro, who has set the target of climate neutrality by 2035. In most of these cases, this refers to scope 1 and 2 emissions, although this is not always clearly defined. Dow furthermore includes scope 3 emissions and product benefits in their carbon neutrality target. However, of these, only BASF and Covestro have published some kind of quantitative roadmap for how these targets are to be reached, and LyondellBasell industries similarly shows this in their sustainability report. These roadmaps are however not as detailed as the other roadmaps included in this report, and will therefore only be briefly summarized here. The focus for reducing emissions in the company roadmaps is primarily on the energy-related emissions, as described below:

- The BASF roadmap presentation *Our journey to net-zero emissions 2050* (BASF, 2021) contains indications of which strategies are to be used to reach 25% emission reduction by 2030 compared to 2018. The path from 2030 to 2050 is not specified. More than half of the reduction until 2030 will be due to renewable electricity and heat electrification measures. The use of new technologies like electric steam cracking, water electrolysis, methane pyrolysis and CCS make up about 20% of the reduction. Optimizations and emissions offsetting make up the remaining emission reduction. The use of bio-based feedstock plays a very marginal role.
- The 2021 sustainability report of LyondellBasell Industries (LyondellBasell, 2022) presents an emission reduction of 30% until 2030 compared to 2020. Here, planned greenhouse gas reduction projects such as minimizing flaring, fuel switches and energy use optimizations make up about half of the emission reduction. Renewable electricity makes up about 20% of the reduction and the rest is not specified.
- Covestro presents their planned emission reduction in their presentation *We Will Be Fully Circular* (Covestro, 2022). A 60% emission reduction is to be achieved until 2030, consisting of 40% renewable electricity, 30% renewable steam and 30% more sustainable manufacturing. The remaining emissions are reduced until 2035 in a similar pattern. More sustainable manufacturing here refers to the use of catalysts to reduce nitrous oxide emissions, energy optimizations and more digitalization for more efficient production control.

3.2.1.2 Strategies for feedstock

In the selected roadmaps, the overall production volumes in Germany are expected to remain stable or decrease by up to 40% until the target year, with an exception for specialty chemicals in *RoadChem* which are there expected to increase by 2% per year in value. To supply the feedstock needed, all available options for feedstock defossilization are used in the roadmaps, i.e., recycled feedstock, biomass-based feedstock as well as feedstock based on captured CO_2, as can be seen in **Error! Reference source not found.**. Especially for CO_2-based production, the addition of hydrogen is required. Some fossil feedstock is assumed to remain in some of the scenarios. Often, the strategies are used in combination, although routes based on captured CO_2 and hydrogen tend to dominate in the German scenarios.

Table 3-3: Feedstock used in the pathways, as shares of total feedstock base for the products specified in the roadmaps

Roadmap	Scenario	Fossil	Recycling	Biomass	CO_2 and H_2
Wege	(All scenarios)	0%	nq	22%	78%**
RoadChem	Technology pathway	46%	12%	29%	14%
	GHG neutrality pathway	6%	11%	28%	55%
KlimaPfade	Proposed path	0%	30%*	0%?	70%
Langfrist	TN-Strom	0%	nq	0%	100%
	TN-H_2	0%	nq	0%	100%
	TN-PtG/PtL	0%	nq	0%	100%
DenaLeit	KN100	19%	nq	9%	72%

*Notes on the table: A deeper color corresponds to a larger share and yellow is used if the feedstock source is mentioned but not quantified. *18% mechanical recycling, 12% chemical recycling. **Other renewable than bio-based is not further specified in the report and subsumed here under CO2/H2*

Recycled feedstock is generally considered an important part of a future circular economy, although not always quantified as part of the feedstock as recycling is considered separate from the chemical industry. All roadmaps refer to increased mechanical recycling, collection rates or material efficiency. Furthermore, RoadChem and KlimaPfade explicitly point to chemical recycling in the form of pyrolysis or a mix of pyrolysis and gasification. Recycled feedstock represents 10 to 30% of the feedstock in the cases where it is explicitly considered.

The use of biomass for feedstock is mixed, ranging from 9 to 30% of feedstock but also 0% in other scenarios, and 40% of the methanol in DenaLeit. It can also be difficult to distinguish its use from carbon capture and utilization (CCU), since the carbon source in platform chemicals is sometimes lumped together, or bioenergy with carbon capture and utilization (BECCU) is used. In the two cases where it is quantified, the technology used is gasification.

The main source of carbon used in all of the German roadmaps is CO_2. In total, captured carbon makes up 14 to at least 72% of the feedstock used, or 55-72% when only net-zero scenarios are considered (mechanical recycling is in most cases not counted here). The CO_2 is most often sourced from air, but industrial sources are also often used, including waste incinerators and district heating as well as the cement industry. Some of the roadmaps (Wege and KlimaPfade) also open up for capture from fossil sources, at least temporarily. The feedstock is in many cases assumed to be imported in the form of synthetic naphtha or methanol from places with presumably better access to cheap renewable electricity. The origin of the carbon is then not always clear, although DenaLeit states that direct air capture (DAC) is preferred. As CO_2 contains no energy, hydrogen must be added, and large amounts of renewable electricity are needed to produce carbon neutral hydrogen through water electrolysis. While green hydrogen production through water electrolysis is the most common technology assumed, methane pyrolysis and steam methane reforming (SMR) hydrogen production equipped with carbon capture are part of one roadmap each.

The subsequent production processes of feedstocks into hydrocarbons are partly independent from the feedstock. The most common routes assumed are to either make methanol, which can then be turned into a variety of chemicals via Methanol-to-Olefins (MtO) or Methanol-to-Aromatics (MtA) routes, or to produce synthetic naphtha by turning the feedstock into syngas by the addition of hydrogen and using it in Fischer-Tropsch (FT) plants. The synthetic naphtha, which is one target product of the FT processes next to hydrocarbon fuels like kerosene is then used in conventional steam crackers. The route with synthetic naphtha thus allows for the continued use of available plants and infrastructure.

3.2.1.3 Strategies for electricity, heat and steam

Most roadmaps foresee a reduction in energy demand from the chemical sector, down to a 35% reduction in the *TN-Strom* scenario in *Langfrist* (there referring to final energy use only), but it may depend on whether e-fuels are counted in terms of energy content or electricity needed for production. Only *RoadChem* includes electricity needed for the production of hydrogen, and presents energy both for final energy use and for feedstock, and projects a 87% increase in this energy demand. Most of the energy demand in the chemical industry is assumed to be supplied in the form of electricity, as can be seen in **Error! Reference source not found.**4, which presents the energy sources used for power and heat. The electricity is modelled to be fully renewable by 2045 in order to be in line with the German emission goals, and is then almost exclusively produced via on- and offshore wind as well as solar photovoltaic (PV). Electrification of chemical industry processes is described through the use of heat pumps, electrified boilers, furnaces (including in some cases steam crackers). While electricity is the main source of energy in all scenarios except one (which focuses on PtG/PtL), this is supplemented by smaller shares of biomass or biogas, or electric fuels (i.e., hydrogen and synfuels). The fuels that can be used depend on the temperatures required, where biogas, hydrogen or synfuels may be used for higher temperatures. Boilers may also be operated flexibly, able to accept a variety of fuels. For lower temperatures, district heating plays a role as well, contributing 5 to 10% of the energy demand. Apart from the defossilization of fuels, all roadmaps also assume energy efficiency gains, for example through conversions to best available technologies (BAT).

The energetic use of hydrocarbon by-products, which is today a very important source (see *Figure 2-2*) may shrink due to increased carbon recycling at the sites, but its potential future role is in general hardly addressed by the studies.

Table 3-4: Energy sources used for non-feedstock purposes in the scenarios, as shares of total non-feedstock energy use

Roadmap	Scenario	Change in final energy demand	Fossil	Waste material	Biomass	H_2	Electricity	Other/ Non-separable
Wege	GreenLate	+11%*	0%	nq	0%	nq	82%	18%
	Other scenarios	-21%*	0%	nq	0%	nq	74%	26%
KlimaPfade	Proposed path	-22%	0%	2%	11%	2%	76%	8%
Langfrist	TN-Strom	-35%*	1%	0%	0%	0%	88%	12%
	TN-H_2	-34%*	1%	0%	0%	29%	60%	11%
	TN-PtG/PtL	-14%*	0%	0%	0%	0%	34%	66%
DenaLeit	KN100	+5%	5%	0%	17%	16%	50%	12%

*Notes on the table: A deeper color corresponds to a larger share. Yellow is used if the energy source is mentioned but not quantified ("nq"). Hydrogen and synthetic fuels are in all cases counted in terms of the fuels' energy content. *Compared with reference value for 2018 given by DenaLeit, as no current value was given in Langfrist and Wege. Any differences in scope were assumed minor and have not been further considered*

3.2.1.4 Timelines

A central question in the discussion is timing. When could potentially the technologies be available, the necessary infrastructure be in place? When are which investments needed? When then can the new technologies start to contribute significantly to production, the emissions significantly decrease and reach net-zero? While some indications of possible timelines are given in the roadmaps (see **Error! Reference source not found.** and **Error! Reference source not found.**), the questions around when things can happen depend on external factors as well, and still remain partly open.

The clearest indications for timing given in the roadmaps concerns when technologies are assumed to be available (**Error! Reference source not found.**). The roadmaps indicate that the period around 2025 to 2035 will be a time when many technologies come into use in general, and by 2040 all the technologies are expected to be available. For specific technologies or strategies, the assumptions are spread, especially when more roadmaps outside the scope of this report are considered (indicated by the green bars in **Error! Reference source not found.**). It can be noted that none of the German roadmaps give an indication of when hydrogen could be used for energy purposes, or when CCS may come into use in the chemical industry. The availability of these options is not about TRL but about related infrastructure needs, that have to be built up. So their phase-in is highly driven by the duration of public planning processes. Furthermore, the production of hydrogen via methane pyrolysis ("turquoise hydrogen") was only indicated in RoadChem, for 2040. Following the market introduction of the technologies, a rapid scale-up is needed, i.e., 10 to 15 years in order to be able to reduce emissions to net-zero by 2045. Indeed, the emissions are modelled to decrease more rapidly after 2035 in several scenarios, even though some also foresee a linear decrease.

As for the development of emissions, the roadmaps portray a linear decrease towards net-zero, or a slower initial decrease followed by an accelerating decrease (see **Error! Reference source not found.**).

The federal law on climate protection foresees a reduction of scope 1 emissions in the total industry sector by 37% until 2030 compared to 2015. Only in the most ambitious pathways displayed, the chemical industry would deliver an equivalent share, in the other pathways other industrial sectors would have to compensate for the slow start of the chemical sector towards decarbonization.

In the German context of Energiewende, there are also intermediate targets set for the energy system, including the phase out of coal until 2038, and a target of 80% renewable electricity by 2030 (compared to 46% today) (Die Bundesregierung, 2023). Achieving these targets will lead to reduced scope 2 emissions for the industry until the next decade.

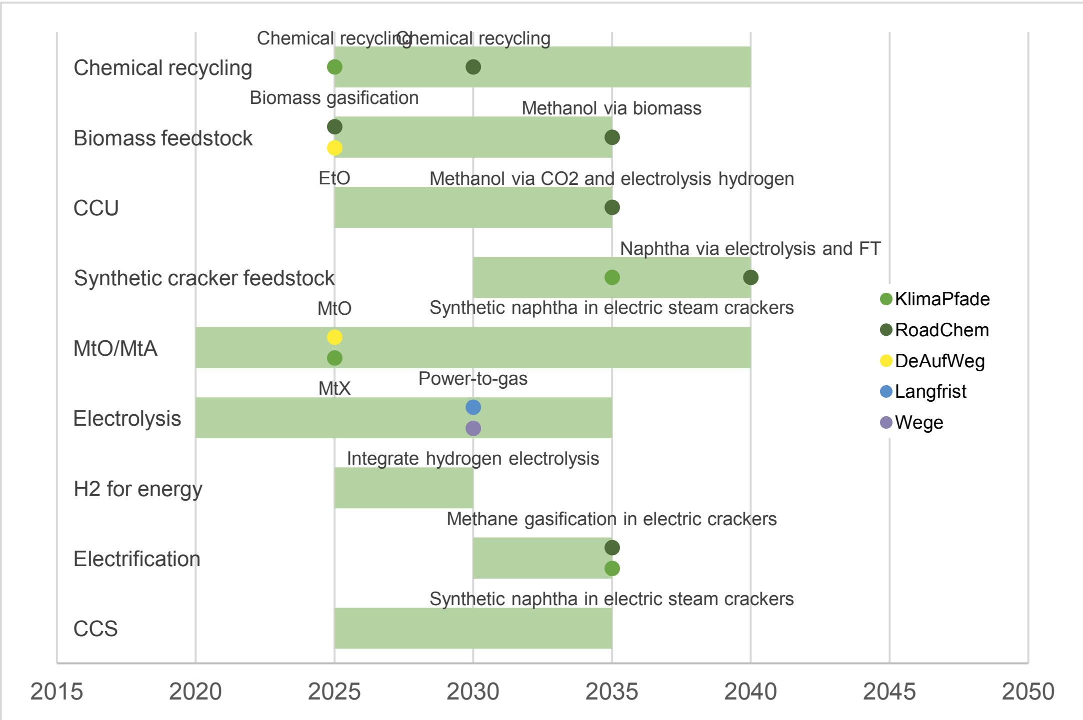

Figure 3-1: Timeline indications for key technologies given in the German roadmaps
Note: The bars represent the span for when technologies of the given category come into play based on a wider selection of roadmaps (e.g., not only with a German scope).

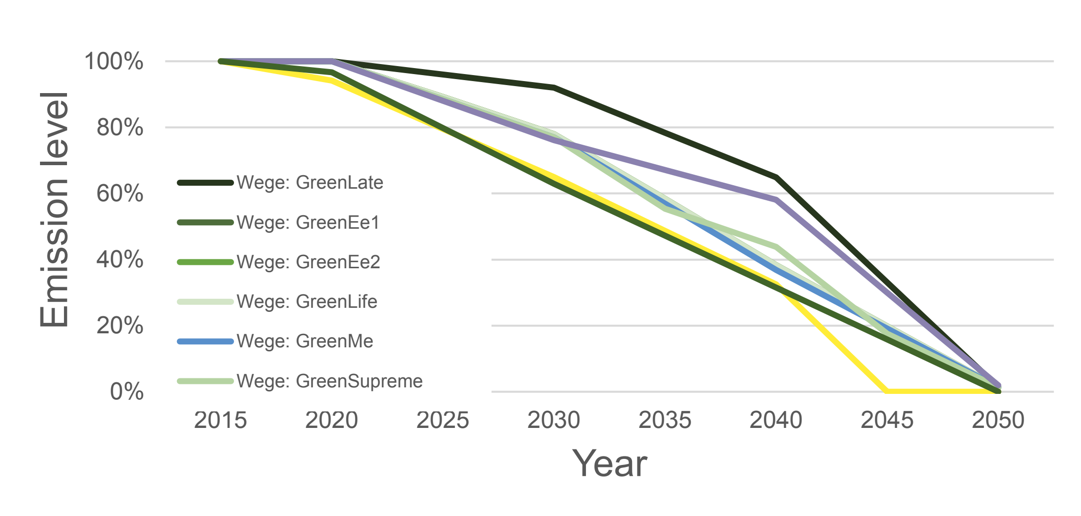

Figure 3-2: Emission development in the German scenarios

3.2.1.5 Challenges identified in roadmaps

The transformation of the chemical industry, which is currently completely dependent on fossil resources both for energy and feedstock, is recognized as a large undertaking in the German roadmaps, and the speed needed to reach the goals until 2045 brings the challenge to a head.

A transformation to a climate neutral chemical industry is naturally associated with significant investment costs to convert all production and furthermore to build up the necessary infrastructure. To make the necessary investments into production units that are intended to be used for decades, the roadmaps suggest that the business case should be clear and with limited uncertainty, unlike today. Failure to reach a business case for a low-carbon chemical industry implies a risk of relocation, where industries move abroad to countries with better economic incentives for chemicals production, be it low-carbon or not. The roadmaps note some challenges in particular that must be overcome. These concern especially investments, price signals, competitiveness, infrastructure, and uncertainties about future conditions. KlimaPfade and Langfrist for example point out that the price structures currently favor the use of natural gas over electricity for heat. The price for natural gas in Germany in 2030 is assumed in KlimaPfade to be 44-62 €/MWh, compared to 64-170 €/MWh for power-to-heat solutions. The range for natural gas price reflects dependency on the CO_2 price, and the cost for power-to-heat is dependent on the user. RoadChem and KlimaPfade emphasize the challenge of transforming the electricity system, which is still far from delivering the required amounts of renewable electricity. They assume an electricity price of 40-50 and 64-174 €/MWh respectively, while the price today is 149 €/MWh (Statistisches Bundesamt (Destatis), 2022), when fossils still represent 47% of electricity production in Germany in 2021 (Eurostat, 2022). Furthermore, the necessary infrastructure for e.g., electricity, hydrogen and CO_2 is not in place, which DeAufWeg, Langfrist and especially KlimaPfade describe. Such infrastructure must be rapidly expanded on a large scale, both on a national and European level. Uncertainties regarding local connections to these infrastructures also complicate planning. At the same time, the three mentioned roadmaps point to the finding that the price signal for CO_2 is not strong enough on its own and not currently effective enough to make the low-carbon alternatives more affordable. DeAufWeg for example states that the CO_2 price should be above 100 €/tCO_2 in the medium term for CO_2-neutral processes to be operated economically (although this is not specific for the chemical industry). All of this is to be done while simultaneously maintaining the competitiveness by providing support and subsidies for targeted investments. To conclude, the roadmaps point to their finding that the current framework does not sufficiently encourage a large-scale transformation and the long-term certainty needed is not in place.

3.2.1.6 Policy recommendations in roadmaps

Several recommendations for policy and government actions are presented to overcome the challenges and enable the described developments. Firstly, the direction of transformation can be set more clearly by government actors, and long term-commitment is needed. This comes for example in the shape of developing strategies for the use of resources like sustainable biomass, and planning infrastructure for e.g., electricity, hydrogen and CO_2, as well as energy management and efficiency. There is also a strong emphasis on increasing resource efficiency and circular economy, for example through increased recycling targets and quotas for recycled input content. The direction would also be set clearly with a carbon price with a high steering effect. On the one hand, the price should be high enough to shift the balance in favor of low-carbon technologies, but on the other hand the industry should not be made uncompetitive, and competition should be fair between industries as well as countries. Some roadmaps argue that the European Union Emissions Trading System (EU ETS) be expanded to sectors currently outside the system. At the moment, there are insufficient incentives through EU ETS to use or produce biopolymers.

Overall, the roadmaps call for increased and long-term engagement by governments in the industrial transition. This both through stronger coordination and enabling faster processes when it comes to planning and approval, but also through success control, monitoring and impact assessment of targets and regulatory frameworks. The transformation also requires long-term financial commitment and speed in technological development. Therefore, several documents also mention more targeted and focused support for technology development.

As long as industries in the EU face different requirements and costs than in other countries, the playing field is not levelled and unfair competition becomes an issue. Policy recommendations in the roadmaps are also directed at addressing this, and to ensure a business case for low-carbon technologies. As the electricity price is a main issue determining future economic viability, reducing this price is especially brought forward, where for example tax exemptions and changes to electricity levies are suggested, alongside the expansion of renewable electricity production. Green Power Purchase Agreements (PPAs) are also promoted. Other tools often mentioned to counteract the business case imbalance of conventional technologies compared to low-carbon are Carbon Contracts for Difference (CCfD) and green lead markets. CCfDs (i.e., contracts, in which the government agrees to pay a company for the difference between the cost of a carbon neutral and the conventional technology, or at least between the emission abatement cost of a new technology and the market price for carbon) could be used for energy carriers for electricity, hydrogen, biomethane and products, especially up to 2030, but the framework around it would still need to be developed. Green lead markets can be used to create demand particularly for the low-carbon products. This can be in the form of quotas for low-carbon material inputs and of creating demand via public procurement. Finally, global harmonization is promoted, through the continued development of the carbon border adjustment mechanism (CBAM) and working harder for an internationally coordinated climate policy.

3.2.1.7 Outlook on discussions beyond the roadmaps

A large range of discussions and topics interplay with that of chemical industry defossilization, such as industry strategies, energy system and circular economy. Here we will elaborate on a few topics that are especially high on the agenda today and have a large impact on the situation in the chemical industry and its transition. These are: the ongoing energy crisis, shifts in the global playing field due to the Inflation Reduction Act in the USA, and developments regarding a hydrogen economy.

The ongoing energy and gas crisis in Europe due to Russia's invasion of Ukraine has put a strain on the European industries, and the German chemical industry not least. The energy prices in Europe have always been considered high compared to other world regions (but for natural gas lower in comparison to East Asia), and are now higher than ever. Furthermore as described above, many of the German clusters are highly dependent on natural gas. The chemicals and pharmaceuticals industry is responsible for 15% of Germany’s gas consumption and the German chemical industry has had a just under 50% reliance on Russian natural gas (Sabadus, 2023). The high gas and electricity prices have caused some chemical industry capacity to close, and the industry’s margins are harmed by the volatile oil and feedstock prices. The fertilizer production, being very gas intensive, has been especially subject to capacity closures. The petrochemical industry is mainly dependent on natural gas for heat and electricity, but certain petrochemical products are also especially affected (Sabadus, 2023). Cefic released a position paper in October 2022 with regards to the energy crisis (Cefic, 2022b). In it, they highlight the trade deficit as the EU imports more chemicals than it exports, and call for action by the European Commission and Member States. They there ask for both emergency measures for the winter, and long-term measures for 2023 and beyond. In November 2022, the European Commission proposed a plan to accelerate renewables permitting processes as a measure to decrease dependence on Russian energy (European Commission, 2022c). At the end of 2022 (in particular in December), chemical production indices fell dramatically and BASF, being most hit by the high gas prices, announced additional plant closures in February 2023, including the permanent closure of one ammonia plant and the closure of a brand new TDI (polyurethane precursor) plant in Ludwigshafen (BASF, 2023). The recent decrease in the price of natural gas and oil (early 2023) has somewhat relieved these strains, but the price is still higher than before the crisis. However, the price of electricity did not decrease as much yet, which has worsened the economic disincentives for electrification. The further direction that these energy prices take in the next years remains uncertain.

Another major point of discussion is the US Inflation Reduction Act of 2022 (IRA), which was passed and signed into law in August 2022 (H.R.5376 - Inflation Reduction Act of 2022, 2022). This record size climate bill attempts to decrease the greenhouse gas emissions from the USA, avoid negative impacts on people due to climate change and the energy shift, while simultaneously making the USA and its industry into a green technology center globally (The White House, 2023). It is filled with subsidies and tax credits for a range of climate and energy related activities, including renewable electricity, manufacturing of clean vehicles, carbon removal, energy efficiency, clean hydrogen, and energy infrastructure in the USA (Boehm, 2023). Due to the global nature of the industry markets, such a bill affects the industries in Europe as well, and here high concerns have been raised by businesses and policy makers. Certain parts of the IRA law has been said to discriminate against European companies, unfairly tilting the global level playing field towards the USA at the expense of the EU, and fears of a trade war and a subsidy race have been voiced (Lee & Klevstrand, 2022; Reuters, 2022). The EU launched a task-force to address concerns by the EU regarding the IRA (European Commission, 2022a), and the EU has since required amendments. On the other hand, the director of Cefic has brought up the IRA as a model for the EU to emulate (Lopez, 2022). They point to the business case the IRA creates for green technologies in the USA, and that the EU ETS and CBAM are flawed and do not retain competitiveness in the EU. They also argue that the state aid rules should be revised to not prohibit subsidies and tax breaks, which the European Commission is now also considering (Kurmayer, 2022).

The crucial development of a hydrogen economy has seen some recent progress. On an EU level, rules have recently been proposed defining what should be counted as renewable hydrogen, in particularly clarifying in what way the electrolyzers must be connected to additional renewable electricity production, an how the hydrogen production should correlate to electricity production temporally and geographically (European Commission, 2023). There are also intensified international cooperations between the EU and other countries on this topic. A cooperation between the EU and Japan has been intensified, aimed at promoting innovation and the development of a global hydrogen market (European Commission, 2022d), and the presidents of the European Commission and Egypt have also issued a joint statement on an EU-Egypt cooperation on renewable hydrogen (European Commission, 2022b). Germany will be investing 550 million € into two hydrogen funds, that aim at fostering investments into hydrogen in developing and emerging economies, as well as accelerating a global green hydrogen infrastructure and market across all countries (BMWK, 2022).

3.2.2 Conclusions on German pathways

There are a variety of roadmaps for Germany tackling the defossilization of the chemical industry. While the chemical industry is often not the main focus, it is an important part of the energy system as a whole. Based on the analysis of these roadmaps, a few conclusions can be drawn, but there are also many questions left unanswered.

The preferred strategy for defossilization of the German chemical industry appears to be a mix of different feedstock and energy options, but there is an emphasis on CCU for feedstock and electricity for energy supply. As domestic resources of renewable energy and feedstock are limited, imports in terms of intermediate products and possibly hydrogen play an important role. The German “industry business model” as a whole is dependent on global markets, and so is its industrial transition.

A priority in the German context is that the system should ideally not only be low-carbon, but also defossilized and renewable. This is true for the electricity, as well as the hydrogen, and means that for example nuclear power or blue hydrogen is mostly avoided in the roadmaps, which is probably due to acceptance issues around these two topics in Germany. On a similar note, concern is given to the use of biomass by emphasizing that it must be sustainably sourced.

While there are several roadmaps pointing a way towards net-zero emissions for Germany, this does not imply that such a development is likely at current conditions. Rather, the documents intend to show what a development in line with the national and international targets could look like, but often emphasize the associated challenges and need for more action if it is going to be realized. The roadmaps are also filled with uncertainties and show deviating results, indicating that the path forward is all but clear for the involved actors and stakeholders. Such open questions include what the future market prices for electricity and other important resources will be, to what extent biomass could and should be used, how fast low-carbon technologies can be put into use and sufficient quantities of green hydrogen and PtX/PtL will be available in sufficient quantities at competitive costs, and consequently if and where low-carbon production can be competitive.

On top of it all, the German industries are currently experiencing several different fundamental movements due to world politics, both challenging and enabling. The vulnerabilities of the natural gas dependent industries have been made clear during the energy crisis, which has forced the natural gas dependent industry to large capacity closures. Also, the competitiveness for green production in the long term could be challenged by the new IRA law in the US, although at the same time, the IRA is sometimes seen as an opportunity to motivate political changes that enable a green transition of European industries. Furthermore, advances are being made to build up the necessary infrastructures and markets for low-carbon solutions, including a global hydrogen economy, and Germany and its industries are active players in these developments.

3.3 Japan

3.3.1 Analysis of roadmaps

This section provides a brief overview of the five strategies selected by Japan. Selected strategies are not necessarily directly indicated for the (petro)chemical industry. Therefore, this section discusses the strategies related to the decarbonization of raw materials (feedstocks), electricity, and heat (steam), which are sources of CO_2 emissions. We then summarized their relationship to the timeline for the emission reduction and strategies, challenges identified in roadmaps, and outlook on discussion beyond the roadmaps from the perspective of policy recommendations.

3.3.1.1 Overview of roadmaps

Energy Saving Technology Strategy (METI & NEDO, 2019)

The first edition of the Energy Saving Technology Strategy was published by METI (Ministry of Economy, Trade and Industry, Japan) in April 2007. This strategy set a goal of "further improving energy consumption efficiency by at least 30% by 2030," and provided guidelines for specific directions to achieve this goal. Subsequently, the guidelines have been revised sequentially under the joint names of METI and NEDO (New Energy and Industrial Technology Development Organization, Japan), while reflecting government policies such as the Basic Energy Plan. Since there are so many energy saving technologies in a wide range of fields, the guidelines identify priority fields and key technologies to be focused on to more effectively promote technology development.

In the 2019 revision, energy saving technologies that lead to the use of waste heat and renewable energy as main power sources are identified as important technologies. Specifically, to promote the use of waste heat and the decarbonization of heat systems, technologies that convert waste heat into electricity with high efficiency and high-efficiency electric heating technologies are added to the list of important technologies. These technologies include high-efficiency power conversion of waste heat, circulating use of thermal energy, and high-efficiency electric heating (dielectric heating, laser heating, and heat pump heating).

In addition, based on the emergence of new business models that utilize digital technology and the rapid increase in the volume of information in recent years, technologies related to the 4th Industrial Revolution have been added to the list of important technologies. These include next-generation processors (neuromorphic and quantum computing), car and ride sharing, and blockchain.

Based on the policy of making renewable energy the main source of power, technologies related to the power supply and demand adjustment and reserve capacity have been added to the list of important technologies. These include grid-side/business and industrial high-efficiency power generation technologies that ensure flexibility, and the adjustment of electricity supply and demand (high-performance storage batteries).

Currently, a revision of the energy saving strategy is under consideration based on the Sixth Basic Energy Plan announced in 2021.

The Sixth Basic Energy Plan and Long-Term Energy Supply and Demand Outlook (METI, 2021a, 2021c)

The S+3E perspective is important in promoting energy policy. S+3E refers to the realization of a system that can supply energy stably (Energy Security) and at low cost (Economic Efficiency) on the premise of safety (Safety), and aims for environmental compatibility (Environment).

Based on this belief, the Sixth Basic Energy Plan was formulated on October 22nd, 2021, which sets the basic direction of energy policy. The year 2021, when this plan was formulated, marks exactly 10 years since the Great East Japan Earthquake and the accident at TEPCO's Fukushima Daiichi Nuclear Power Plant. The focus of this master plan is to chart a course for energy policy toward achieving "carbon neutrality by 2050," as announced in October 2020, and a new mid-term greenhouse gas (GHG) emission reduction target, as announced in April 2021. The new GHG emission reduction target is a 46% reduction in GHG emissions by 2030 compared to 2013 levels. The report also mentions that, in order to overcome the challenges posed by Japan's energy supply and demand structure while promoting climate change countermeasures, efforts will be made to ensure a stable supply and reduce energy costs, with safety as a major prerequisite.

And the Long-Term Energy Demand and Supply Outlook is a strategy released in conjunction with the Sixth Energy Basic Plan. It lays out a concrete path for a 46% reduction in GHG emissions. In other words, it shows how to overcome the various challenges that will arise in energy supply and demand as a result of attempts at thorough energy conservation and aggressive use of non-fossil energy, and what the structure of energy supply and demand will look like at that time.

According to the Long-Term Energy Supply and Demand Outlook, primary energy supply is expected to be about 430 million kL of crude oil equivalent (about 16,400 PJ), almost unchanged from the current situation. The breakdown is as follows: 31% oil (about 5,000 PJ), 22-23% renewable energy (about 3,800 PJ), 19% coal (about 3,000 PJ), 18% natural gas (about 3,000 PJ), 9-10% nuclear power (about 1,500PJ), and 1% hydrogen/ammonia (about 2 million kL, 76 PJ).

Roadmap for Carbon Recycling Technologies (METI, 2021b)

CO_2 is treated as a source of carbon, it will be utilized for producing chemical materials and fuels, mineralization source, etc. and it will also be able to control CO_2 emissions. Carbon Recycling technology advances research and development of CO_2 utilization promoting collaborations among industries, academia and governments around the world and stimulates disruptive innovation. The strategy outlines the direction of technology development for 2050 and beyond, and includes performance and cost targets for individual technologies.

This strategy was developed in June 2019, but was revised in July 2021 due to rapid progress in R&D aimed at international collaboration and the "Green Growth Strategy Associated with Carbon Neutrality in 2050," discussed below, which was developed in December 2020 and positions carbon recycling as a key technology for achieving carbon neutrality.

Specifically, DAC (technology for direct capture of CO_2 from the atmosphere) and synthetic fuels (carbon-free decarbonized fuel produced by synthesizing CO_2 and hydrogen), which have made remarkable progress, were newly added to the roadmap.

And until now, the roadmap had set "around 2030" for (1) those aiming for early deployment (those that do not need hydrogen or have high added value) and "around 2050" for (2) mid- to long-term deployment (general-purpose products). In the revised version, (2) above has been moved forward to "around 2040" in view of the progress and acceleration of development. In addition, the details of efforts for international collaboration, which has been progressing, have been added.

Green Growth Strategies Associated with 2050 Carbon Neutrality (METI, 2020)

Achieving a carbon neutral society cannot be accomplished without extraordinary efforts. Therefore, in order to encourage innovation that encourages bold investment, the government has decided to allocate a generous budget to 14 selected areas that are expected to grow. No areas specific to the chemical industry have been selected, but technology development related to raw materials, electricity, and heat have been selected. The 14 areas include (1) renewable energy, (2) hydrogen and ammonia, (3) heat utilization, (4) nuclear power, (5) automobiles and storage batteries, (6) semiconductors and information and communications, (7) ships, (8) logistics, human flow and infrastructure, (9) food, agriculture, forestry and fisheries, (10) aircraft, (11) carbon recycling and materials, (12) housing, construction and power management, (13) resource recycling and (14) lifestyle.

Keidanren Carbon Neutral Action Plan - Vision toward Carbon Neutrality by 2050 and Fiscal 2021 Follow-up Results (Performance in Fiscal 2020) (Keidanren, 2022)

The Japan Business federation (Keidanren) consists of 1,494 representative Japanese companies, 108 major industry associations in the manufacturing and service sectors, and 47 local business organizations. They aim to develop the Japanese economy and improve people's lives by harnessing the vitality of companies and the individuals and communities that support them. They propose steady and prompt measures to address the various economic and industrial challenges facing the country, while compiling their views on the issues.

It also encourages domestic industries to formulate a vision (basic policy) for the realization of a carbon neutral society in 2050. Therefore, they call for efforts to effectively reduce CO_2 emissions through the maximum adoption of BAT (Best Available Technologies). Then, to achieve the goal of GHG emission reduction in 2030, the progress of each industry is surveyed every year, and the direction is reviewed and revised. The survey report is the Carbon Neutral Action Plan submitted by each industry section.

The Carbon Neutral Action Plan for the petrochemical (chemical industry) sector is compiled by the Japan Chemical Industry Association (JCIA) and reported to Keidanren. According to the JCIA, in its Carbon Neutral Action Plan for the Chemical Industry, the chemical industry section aims to reduce CO_2 emissions by 20 million tons (equivalent to 32% reduction) by 2030 on a fiscal 2013 basis. Furthermore, for 2050, the plan sets a goal of introducing innovative technologies to achieve carbon neutrality, such as technology to produce plastics from CO_2, artificial photosynthesis, and positive use of biomass.

The JCIA has proposed its own life cycle analysis (LCA) assessment index, cLCA (carbon life cycle analysis), for the treatment of CO_2 emitted when chemical products are used by other industries or consumers. This method estimates the reduction in CO_2 emissions by adding up the amount of CO_2 emitted in each process of raw material extraction, manufacturing, distribution, use (consumption), and disposal, and comparing it to the amount of CO_2 emissions if existing products were distributed. This concept will be applied not only in the chemical industry, but also in the fields of steel and cement as well as synthetic fuels in the future.

In May 2021, the JCIA published "The Chemical Industry's Stance Toward Carbon Neutrality" (JCIA, 2021). It advocates rationalization of product manufacturing processes, introduction of innovative technologies such as electrification, fuel conversion for in-house power generation facilities, use of renewable energy, use of biomass, recycling of raw material carbon by utilizing waste plastics, process conversion leading to minimization of energy consumption, and development of new materials worthy of innovation in the entire value chain.

Like JCIA, in March 2021, the Petroleum Association of Japan (PAJ) released its "Vision (Aim) Toward Carbon Neutrality in the Petroleum Industry" (PAJ, 2021). The industry is working on energy conservation measures, such as reducing energy consumption in heating furnaces by using high-efficiency heat exchangers, introducing advanced computerized control systems, and replacing steam turbines with high-efficiency motors as the power source for compressors. Toward 2050, the company is also working to develop innovative technologies, such as promoting the recycling of waste cooking oil and waste plastics, utilizing biomass feedstock, producing sustainable aviation fuel (SAF), and producing synthetic fuels through the production and use of CO_2-free hydrogen. These developments are also described in the carbon neutral action plan mentioned above.

While there are various strategies as described above, the key to reducing CO_2 emissions in the chemical industry is to focus on the sources of those emissions: raw materials (feedstocks), electricity, and heat (steam), and to make them CO_2-free. From the next section, we will organize the strategies and issues mainly from these three aspects.

3.3.1.2 Strategies for feedstock

From Figure 2-5, coal and oil are used as main raw materials in the chemical and petrochemical sector. The amounts are 129 PJ of coal (about 17%) and 341 PJ of oil (about 45%).

The only way to make these raw materials CO_2-free is to convert them to biomass-derived raw materials or to recover CO_2 and produce raw materials for petroleum products from CO_2. In other words, one is to use bionaphtha to produce petroleum products through conventional processes (naphtha cracking), and the other is to produce petroleum products directly from CO_2. The latter is a carbon recycling technology that is being actively researched and developed in Japan; for example, projects are underway in Japan to produce olefins and other products from CO_2. Whether all petroleum products can be manufactured from CO_2 is a major issue for the future, including the balance between supply and demand.

There are also many issues to be considered, such as how long CO_2 will be fixed in petroleum products manufactured from CO_2, how to evaluate CO_2 after disposal, and if DAC is used, whether the mass balance between CO_2 recovery by DAC and supply to products can be maintained.

Incidentally, there have been few attempts to use biomass as a feedstock for the chemical industry in Japan. In December 2021, Mitsui Chemicals imported about 3,000 tons of biomass naphtha (bio-naphtha) from Neste in Finland and fed it into an ethylene cracker at its Osaka Plant. The company plans to produce various plastics, chemicals, and other derivatives from the ethylene cracker. The products will be shipped with biomass certification based on ISCC PLUS (International Sustainability and Carbon Certification) certification. These attempts are just the beginning.

It is an extremely important concept to recycle waste, waste cooking oil, and waste plastics. In Japan, about 85% of plastics are recovered, and the recovery rate is increasing year by year. However, the current breakdown is 22% material recycling, 3% chemical recycling, and 60% thermal recycling. Compared to Europe and other countries, incineration is more widespread in Japan, and thermal recycling is the mainstream. Japan is aiming to increase material and chemical recycling under the Resource Circulation Strategy for Plastics formed in May 2019.

3.3.1.3 Strategies for electricity

There is first of all the need to decarbonize the electricity used for current end-use technologies. In addition, a decarbonized electricity supply would also provide opportunities for electrification of heat (steam), as discussed in the next section. Therefore, this section analyzes the strategies for decarbonizing electricity supply in Japan in general.

Japan's electricity supply is based on a centralized power supply system. On the other hand, many offices have their own power generation systems. This is very reassuring during periodic inspections of factories and in emergency situations such as disasters, but power generation capacity is not very large.

Japan's electricity composition is 31% coal, 6.4% oil, 39% natural gas, 7.8% hydroelectric, and 12% renewable energy (FY2020). It is difficult to know which type of power source supplied the power from the power plant to the factories and other facilities, because the power is connected to the power grid. Japan relies on imports for most of its fuel for power generation, and the composition of that power depends on the location of power plants and factories.

The use of renewable energy sources is essential to decarbonizing electricity. The petrochemical industry consumes 191 PJ of electricity (Figure. 2.2 3), which would require 43 million kW of solar power or 30 million kW of wind power (converted to 14% and 20% of solar and wind power facility utilization, respectively). Currently, solar power is the most widely installed renewable energy source in Japan, with an installed capacity of approximately 65 million kW (in FY2020). In other words, if the power consumed by the petrochemical industry were to be supplied by photovoltaic power generation, it would require an amount of power equivalent to 2/3 of the existing photovoltaic power generation capacity.

To begin with, Japan has limited land with good solar radiation and wind conditions, and Japan does not have a well-developed power transmission and distribution network for renewable energy, and efforts are currently underway to strengthen this network. We must also not forget to take measures to prevent power output fluctuations due to the instability of renewable energies.

CO_2-free electricity supply by means other than renewable energy is also being considered. The key point is how we can get rid of fossil fuels, but we need to think about solid, liquid, and gaseous fossil fuels. For solid fuels, the use of recycled materials such as biomass and waste plastics is mainly effective. For liquid fuels, ammonia and MCH (methylcyclohexane), which are in the spotlight as hydrogen carriers, and methanol and ethanol as CCU products can be considered. For gaseous fuels, hydrogen and synthetic methane as CCU fuels can be considered. This is also true for the strategy for feedstock and for heat and steam.

For hydrogen and ammonia, the Japanese government aims to replace 1% of its power supply mix with hydrogen and ammonia by 2030, and to introduce 20 million tons of hydrogen and 30 million tons of ammonia by 2050 (METI, 2020, 2021a, 2021c).

Since methanol and ethanol again produce CO_2 when burned, it is necessary to consider using the recovered CO_2 as a raw material and recovering the CO_2 after combustion. Of course, using CO_2 recovered from the atmosphere is very effective (DAC), and CO_2 can be isolated by CCS.

In order to construct such a new energy system, NEDO is promoting next-generation R&D that challenges carbon neutrality under the title of "moonshot-type R&D projects" (NEDO, n.d.-a) and "green innovation fund projects" (NEDO, n.d.-b). However, it is likely to take some time before practical application.

3.3.1.4 Strategies for heat and steam

There are three ways to decarbonize heat: (1) effective utilization of unused heat (waste heat), (2) CO_2-free heat sources, and (3) use of electrothermal conversion.

Even though waste heat is generated as a by-product in almost all technical processes, it is often lost without being utilized. For example, incineration of waste materials to generate heat for heating and hot water supply is one of Japan's specialties. Thermal storage technologies, heat pumps, absorption and adsorption chillers, and thermoelectric generators play an important role in the utilization of waste heat. Waste heat can be easily utilized, but the balance between waste heat sources and consumers is very important. In particular, it is necessary to investigate the temperature range, heat content, waste heat flow, timing of heat supply and heat demand, type of heat medium, and local conditions.[1] Effective use of unused heat (waste heat) can significantly reduce fossil fuel consumption and CO_2 emissions. However, as long as fossil fuels are used as heat sources, it is not possible to reduce CO_2 emissions to zero.

CO_2-free conversion of heat sources can be achieved by replacing natural gas, light oil, heavy oil, etc. used as heat sources with CCU fuels, as discussed in section 3.3.1.3.

It is also important to capture the CO_2 emitted after combustion (steam production), unless the CCU fuel is produced with CO_2 by DAC. Alternatively, CO_2 can be isolated by CCS.

In Japan, the development of synthetic methane (e-methane) is becoming active, especially in the gas industry (The Japan Gas Association, n.d.). E-methane is produced by synthesizing hydrogen from renewable energy sources and CO_2 recovered from factories, power plants, and in some cases, the atmosphere, in a methanation reaction. This e-methane can be used immediately as an alternative fuel to natural gas as a heat source in areas of Japan where infrastructure is in place. However, if the CO_2 recovered from a power plant or factory is derived from fossil fuels, it will not become carbon neutral unless the emitted CO_2 is recovered after it is used (burned) as a heat source.

As for the electrification of heat using electrothermal conversion technology, it is seen only in small-scale applications. If it is to be made large scale, there are still major issues to be solved, such as securing large scale electricity from renewable energy sources.

3.3.1.5 Timelines

With only a limited time until 2050, if we want to ensure the realization of a carbon neutral society, we need to make the most effective use of existing technologies and infrastructure while simultaneously developing innovative technologies. The carbon recycling technology roadmap announced by METI indicates that research and development will be divided into three phases as shown in Figure 3-3 (METI, 2021b). Various products can be manufactured from CO_2, but products that can effectively utilize existing technologies and infrastructure will be manufactured in Phase 1 through technology demonstrations and put to practical use in Phase 2. For example, minerals that do not require hydrogen (e.g., concrete), bio-jet fuel and polycarbonate, which are already commercialized, are products developed in Phase 1. In Phase 3, when consumption of these products is expected to expand significantly, synthetic fuels and chemicals, which take time to develop and spread, will be put to practical use. However, discussions on the scale of market introduction of raw materials, fuels, and electricity produced by carbon recycling, necessary costs (cost-effectiveness), and CO_2 reduction effects have not been discussed in detail. This is a major issue, as it is also a factor in corporate management decisions.

[1] For the detail, please refer to another publication from GJETC „Topical paper on the potential of waste heat usage in Germany and Japan“ (Kawamura et al., 2023)

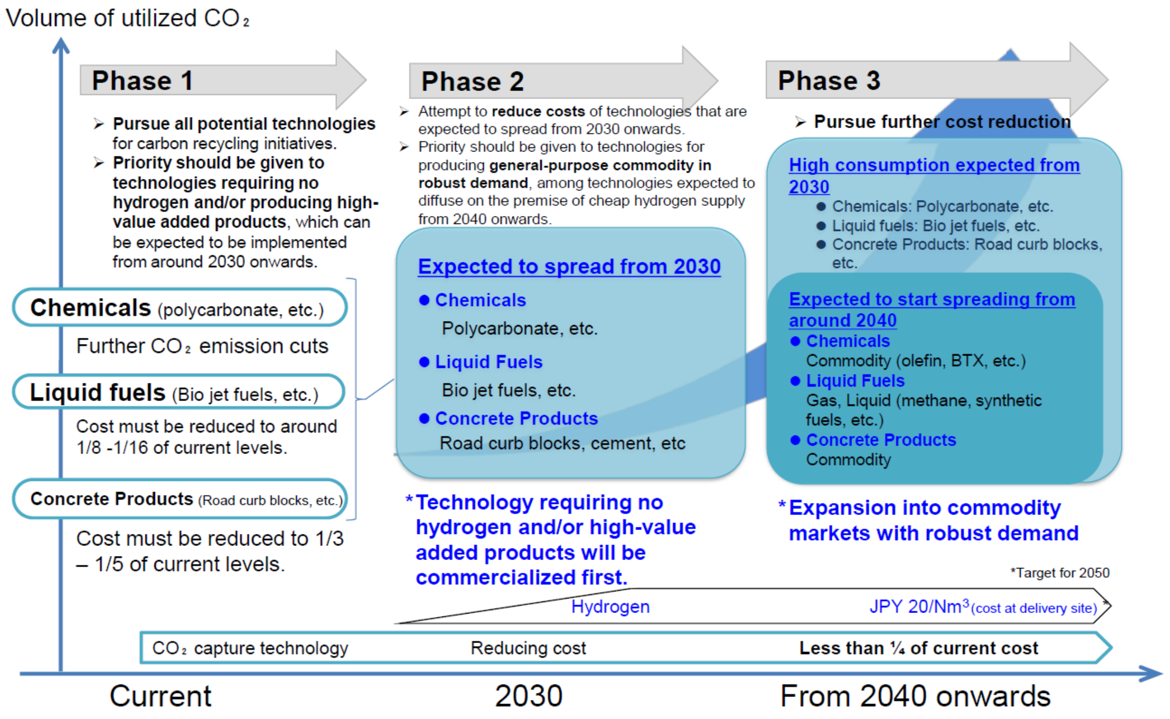

Figure 3-3: Roadmap for carbon recycling technologies
Source: (METI, 2021b)

3.3.1.6 Challenges identified in roadmaps

Technologies for conversion to CO_2-free raw materials, electricity, and heat (steam) already exist in reality and it is scientifically possible to produce them toward carbon neutrality. The Carbon Recycling Technology Roadmap qualitatively suggests what and when to introduce these technologies with respect to a timeline. If realized, it will bring us much closer to carbon neutrality. However, there is much uncertainty about the CO_2 reduction and cost-effectiveness of introducing each technology and CO_2-free products. This has caused companies to hesitate to invest. We hope that these R&D efforts will make a significant contribution to promoting the development of innovative technologies and improving cost-effectiveness in order to bridge the gap between the present and the future vision of a carbon neutral society in 2050.

3.3.1.7 Outlook on discussion beyond the roadmaps

In recent years, major natural disasters have occurred in many countries around the world. Japan is no exception. The global spread of new coronavirus infections caused a major impact on the economy and energy. Above all, Russia's invasion of Ukraine has led to a continuing energy crisis in Japan, Europe, and many other countries, causing energy prices to rise sharply.

Japan has a very low energy self-sufficiency rate, and if supply chains are disrupted due to these effects, the supply of products from petrochemical manufacturers will be disrupted, and the impact on the social economy will be very large. Geopolitical considerations of fossil resources (fuels) have been conducted on various occasions in Japan. Therefore, Japan continues to discuss the correction of overseas dependence on fossil resources (fuels) and the decentralization of production bases. The introduction of carbon recycling technology is essential to realize a carbon neutral society, and renewable energy is the key to this. In other words, it is quite possible that in the future we will be forced to import renewable energy (i.e., depend on overseas sources), so geopolitical considerations regarding renewable energy will also be necessary in the future.

3.3.2 Conclusions on Japanese pathways

Japan is an island nation with a very low energy self-sufficiency rate. Since energy cannot be exchanged with other countries directly and the domestic pipeline network is not well developed, it is necessary to build an energy system based on energy imports by shipping in addition to developing domestic renewable energy sources to the extent possible. Various strategies published in Japan also describe these ideas as their basic premise.

To reduce CO_2 emissions in the chemical industry (petrochemical industry), it is essential to make raw materials (feedstocks), electricity, and heat (steam) CO_2-free. In fact, the energy sources used in Japan's chemical industry (petrochemical sector) can be broadly classified into petroleum, coal, natural gas, and electricity. Something must be done about these.

For electricity, it is important to introduce renewable energy sources, but the amount of renewable energy is not infinite. The stability and amount of electricity generated depends on factors such as solar radiation, wind conditions, and the amount of water as well as available land area and social acceptance of renewable technologies. Considering such constraints and foreseeable technological level, it would most likely not be cost-effective for Japan to meet all its energy needs from domestic renewable energy sources, thus in the future it will need to collaborate with foreign countries (importing renewable energy). This idea is connected to the development of carbon recycling technology. The use of substitutes for fossil resources (fuels) manufactured from CO_2 (CCU products) will greatly reduce the consumption of fossil resources (fuels) used for raw materials, electricity, and heat (steam). Furthermore, to become carbon neutral, it is necessary to capture the CO_2 generated after the CCU product is used, burned, incinerated, or disposed of as waste. Alternatively, CO_2 must be captured from the atmosphere and balanced or sequestration by CCS must be considered.

However, there is much uncertainty about the CO_2 reduction and cost-effectiveness of introducing each technology and CO_2-free products. This has caused companies to hesitate to invest. We hope that current and planned R&D efforts will make a significant contribution to promoting the development of innovative technologies and improving cost-effectiveness in order to bridge the gap between the present and the future vision of a carbon neutral society in 2050.

We are hopeful that energy systems with carbon recycling will play a major role in bridging the gap between the future and the present. We also believe that the introduction of carbon recycling is essential to the realization of a carbon neutral society, and renewable energy and hydrogen are key. In doing so, geopolitical considerations regarding renewable energy and diversification of its supply will also be necessary in the future, because we will be forced to import renewable energy (dependence on foreign countries) in the future.

4 Comparison of industrial context and decarbonization strategies, and key insights

In the overall comparison, we first compare the initial situation of the two countries and then move on the comparison of the roadmaps and their strategic implications.

Table 4-1 presents similarities and differences of the current situation in the chemical industry (petrochemical industry) between Germany and Japan.

Table 4-1: Comparison of the Current State of the Chemical Industry in Germany and Japan

Similarities and common challenges	Differences and specific challenges
Similarities ● Similar size industries ● Mid-century net-zero target ● Limited domestic resources – import dependence	**Differences** ● Land connections to other countries ➢ Different infrastructures affects value chains, dependencies, and closeness to world market ● Energy mix to chemical industry ➢ Gas and oil-derived cracker by-products in Germany ➢ Coal and oil in Japan
Common challenges ● Finding ways forward to reach net-zero targets ● High energy prices	**Specific challenges** ● Germany: Increased gas and power price

The size of the German and Japanese industries is almost the same. And both countries also share the goal of achieving a carbon neutral society by mid-century. Furthermore, both countries are very similar in that we both lack domestic energy resources and rely on imports from abroad. Both countries have experiences with long term contracts for energy supply to hedge against volatile world market prices, but Germany relied much on Russian oil and gas deliveries and has no established structures with trade agencies under supervision of the government. In common, both Germany and Japan are searching for ways to achieve a carbon neutral society and have yet to find a solution, and both countries are challenged by the recent increase in energy prices.

The critical difference between Germany and Japan is their geographical environment. While Germany is connected to its neighbors by land and integrated into two physical cross-border production networks, Japan is an island nation surrounded by the sea. This will have a very significant impact on infrastructure, the construction of supply chains among companies, and affinity with the global energy market, which are essential for achieving a stable energy supply. In Germany, the very large cluster comprising the Rhein-Ruhr area and the two North Sea ports of

Antwerp and Rotterdam form a unique meta-cluster of its own that covers the complete range of standard polymers and is thus capable to react on the usual market imbalances quite quickly, as platform chemicals can be easily exchanged via pipeline and plant utilization rates can be stabilized. Particularly in the case of Japan, energy supply by pipeline is currently not feasible, so the country must rely on energy transport by ship, but the topography of the country also hampers the building of pipeline interconnections within the country, so most of the Japanese chemical sites are distributed to several industrial areas without physical interconnections and are more exposed to the world market. In other words, if Japan wants to be prepared for any contingency, Japan needs to find a diversity of energy sources.

The two countries also differ in their energy sources in the chemical industry. Germany mainly uses natural gas when it comes to fuel use and uses oil-products for heat and steam generation mainly in the form of by-products, whereas Japan relies on coal and oil as well as natural gas. Thus, Germany's chemical industry has been severely impacted by the high prices of natural gas due to the disruption of natural gas from Russia, also for domestic production of grey hydrogen as a feedstock.

An overview of main similarities and differences in the roadmaps is shown in Table 4-2.

Table 4-2: Comparison of German and Japanese Roadmaps to Achieve a Carbon Neutral Society

Similarities	Differences
● Mid-century net-zero targets ● Limited domestic renewable resources compared to demand. (import dependence) ➢ Importing synthetic fuels and feedstocks. ● Focus on recycling as an alternative source for the feedstock	● Roadmaps specificity for petrochemical industry ● Physical connections to other countries ➢ Germany: Power grid, pipelines ➢ Japan: No connections. Transport by ship. ● Non-feedstock energy use ➢ Germany: Green electricity dominant ➢ Japan: Range of imported fuels ● Framing ➢ Germany: Renewable resources to improve sustainability and supply security ➢ Japan: Energy security issue and efficiency

Basically, the characteristics of the environment surrounding the chemical industry are directly reflected in the policies and roadmaps. One is the goal of achieving a carbon neutral society by the middle of this century. Various policy options to enable and encourage this are discussed, such as regulation, carbon pricing including emission trading, and international cooperation. Another similar characteristic is that both countries are densely populated and have less favorable renewable energy resources than other countries. This means that there is a limit to the supply of renewable energy at competitive prices in the countries themselves, and in the future it may make sense to, or they even will have to, rely on imports of renewable energy from abroad as well. Importing renewable energy means not so much electricity, but mainly synthetic fuels and CO_2-free raw materials produced by using renewable energy. Both countries have also investigated strategies for carbon cycling in the form of CO_2 reuse (CCU) and the chemical recycling of plastic waste.

There are also several differences between the roadmaps of Germany and Japan. First, Germany is connected to its neighbors by land, which allows it to source electricity in a greater geographical electricity system and market, which allows for more compensation of regional fluctuations in the supply of renewable electricity. Hydrogen might also be supplied by pipelines from the North Sea or from countries like Spain or even Morocco. Japan, on the other hand, is an island nation surrounded by the sea, and therefore has to rely solely on shipping of energy. Therefore, as a measure to reduce fossil energy consumption (CO_2 emissions) in the chemical industry, Germany is focusing on electrification (this possibly in hybrid systems to add flexibility to the electricity market), while Japan is assuming that CO_2-free energy will mainly be procured in the form of chemical energy carriers overseas and imported by ship.

In Germany, energy security may be achieved by its integration into the European energy markets as well as through diversification of imports of green fuels from overseas, whereas Japan searches to diversify its imports of clean fuels.

Some main differences can thus be explained by their embeddedness into more general overall political strategies. The topic of industrial transition is connected to other strategical objectives and societal developments. This influences the context in which the roadmaps are produced, and thereby the framing of the roadmaps and its measures. For example, the German Energiewende, EU strategies, and targets such as the EU Green Deal puts the German roadmaps in a context focused particularly on complete defossilization and use of renewable resources to improve sustainability and security of supply, with energy efficiency as the second pillar. In the Japanese roadmaps, the context of challenges with energy security and the efficient use of energy receives a comparatively greater focus. While the different priorities may shape which strategies are preferred in the different countries, all issues are part of the discussions in both countries, as they all affect their respective industries to different degrees. It is also an opportunity to draw inspiration from the solutions considered in the different context, and thereby find more robust solutions with greater benefits.

5 Conclusions and recommendations

The findings of this GJETC study on roadmaps for the petrochemical industry can be compared to the similar GJETC study made in 2021, which analyzed potential roadmaps and strategies for decarbonizing the steel industry. That study found that the targets, technologies, and strategies are quite similar in both countries, showing a large potential for cooperation in development of technologies and markets. Compared to the steel sector, this study on the petrochemical industries found that the decarbonization targets are again similar for both countries, but that both the priorities in the technological roadmaps and strategies for decarbonizing feedstocks and energy supply have some major differences, and that even at least within Germany, scenario studies show uncertainties about these priorities. Therefore, cooperation between Germany and Japan may rather need to focus on learning together and from each other, but also on the development of global supply chains for clean CO_2-based hydrocarbons, which play an important role in the strategies of both countries.

Germany can learn a lot from Japan when it comes to diversifying energy supply on the world markets. This learning process has already started – even at the government top level with a visit of the German Chancellor to Japan in March 2023 covering this topic. For the future, a liquid world market for green chemical energy carriers and feedstocks, such as naphtha, methanol, ammonia, and possibly hydrogen, is in the interest of both countries. Here, a better understanding of the future import requirements and possibilities should be developed. While a room for green ammonia is very likely, the future of hydrocarbon supply to the chemical industry is still open. Many countries still consider fossil oil as a future feedstock, where supply might be extremely monopolized in the future due to a very small remaining market. CO_2-based hydrocarbons are discussed in both countries, be it as a fuel or as feedstock. The political incentivization of their use is still not tested at a large scale, and both countries may learn here in regard to the different usage of political instruments.

One interesting question is what kind of green hydrocarbon carriers will be standard commodities of the future. Both countries may learn here together and from each other regarding the use of these new feedstocks and platform chemicals, for example when it comes to technical studies on methanol-based value chains. Both countries could also develop common projects or try to incentivize market creation. During the introduction period, there is a risk of competing interests. However, a first project on a Joint Study Agreement to develop a clean ammonia project in the Port of Corpus Christi in Texas, USA was launched in February 2023 by the German energy company RWE, the Japanese Mitsubishi Corp. and the Korean company Lotte Chemical (RWE, 2023), showing a potential room for cooperation with a risk sharing between these three energy import dependent and world market integrated industrial countries. This is an example of how Germany and Japan could jointly approach and form coalitions with potential importing and exporting countries of future green commodities, while at the same time developing the technologies needed for both production and transport of the clean fuels.

Cooperation and mutual learning may also help to accelerate the market introduction of other key technologies and to fill gaps and uncertainties in timelines. While the Japanese industry has more technological know-how on industrial heat pumps with high supply temperatures, Japan might learn from experiences in Germany in the flexible use of technologies, such as heat pumps and electrode boilers, in highly volatile electricity markets with a high renewable share. Learnings could be on the technical design level for power-to-heat and their integration into hybrid steam supply systems, on the operation level for chemical companies and grid operators, but also with regard to the design of policies, e.g., for the electricity markets or subsidy schemes in order to incentivize an electrification that helps to stabilize the electricity system.

With regard to research and development on new technologies to produce petrochemicals both countries can learn from each other. In Germany, biopolymers might have a stronger focus due the existing potentials in the country, while CO_2 based technologies seem to have a greater focus in Japan. The chemical recycling of plastics to provide a low-carbon feedstock is another important area of common interest to develop.

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