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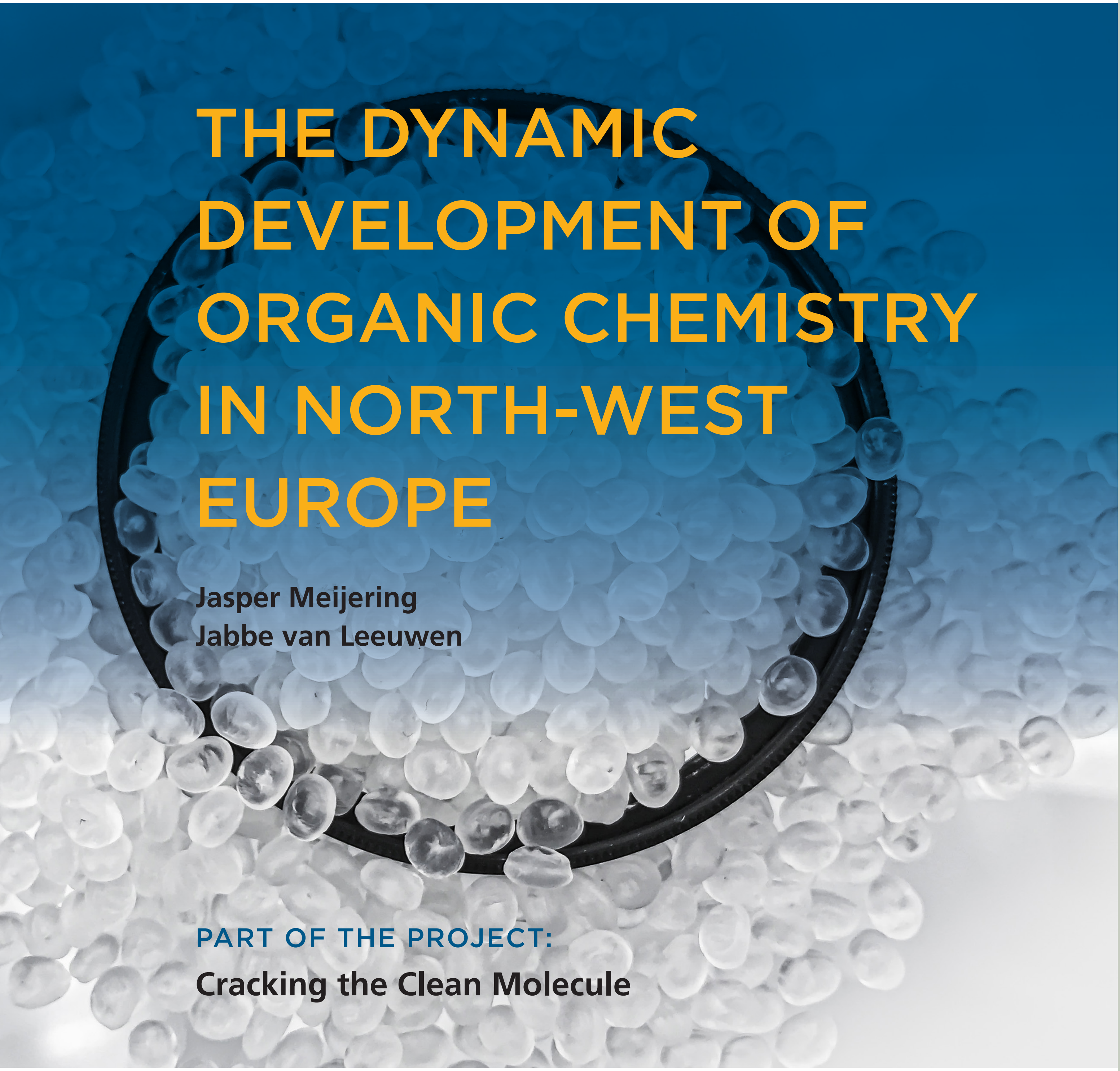

THE DYNAMIC DEVELOPMENT OF ORGANIC CHEMISTRY IN NORTH-WEST EUROPE

Jasper Meijering
Jabbe van Leeuwen

PART OF THE PROJECT:

Cracking the Clean Molecule

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THE DYNAMIC DEVELOPMENT OF ORGANIC CHEMISTRY IN NORTH-WEST EUROPE

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PART OF THE PROJECT:

Cracking the Clean Molecule

In the **'Cracking the Clean Molecule'** ongoing project, the future of organic chemicals production is explored against the background of a society pushing towards net-zero emissions. Its focus is on the prospects of a third feedstock transition in the Antwerp, Rotterdam, Rhine, Ruhr Area (ARRRA) organic chemistry cluster.

This paper lays the foundation by describing the logic behind the ARRRA cluster based on past value chain developments and analysing, from a systems perspective, the interdependencies of present organic chemistry sites in the cluster. This analysis leads to a number of considerations for rearranging institutions found in the ARRRA region, as well as suggestions for the deployment of additional policy instruments. Additionally, this paper provides an analytical basis to evaluate the medium-term prospect of alternative feedstocks for chemical products, which is subject of the next study.

TABLE OF CONTENTS

ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
ARRRA	Antwerp-Rotterdam-Rhine-Ruhr Area
BTX	Benzene, toluene, xylene
CEPS	Central European Pipeline System
COTC	Crude-oil-to-chemicals
CTO	Coal-to-olefins
EPS	Expanded polystyrene
ETS	Emissions Trading Scheme
GHG	Greenhouse gas
HDPE	High-density Polyethylene
IEA	International Energy Agency
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
LPG	Liquefied Petroleum Gas
MB/D	Million barrels per day
MDI	Methylene diphenylmethane diisocyanate
MEG	Mono ethylene glycol
MTBE	Methyl tert-butyl ether
MTO	Methanol-to-olefins
NGLs	Natural Gas Liquids
NWO	Nord-West Oelleitung
PDH	Propane dehydrogenation
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
POSM	Propylene oxide styrene monomer
PP	Polypropylene
PS	Polystyrene
PTA	Purified terephthalic acid
PUR	Polyurethane
PVC	Polyvinylchloride
PX	Para-xylene
RAPL	Rotterdam-Antwerp Pipeline
RC2	Rotterdam C_2 (Ethylene) Pipeline
RMR	Rhein-Main-Rohrleitung
RRP	Rotterdam Rhine Pipeline
SAN	Styrene-acrylonitrile
TDI	Toluene diisocyanate
VCM	Vinyl chloride monomer

FIGURES

BOXES

1 INTRODUCTION

Europe's Antwerp, Rotterdam, Rhine, Ruhr Area (ARRRA) is home to the continent's largest cluster for the transformation of hydrocarbons into organic chemical products. Will this industry soon be independent of oil and natural gas? Based on the introduction of the European Union's (EU) Green Deal – the continent's 'man on the moon moment' – one would be tempted to think so. Moreover, in Germany[1], Belgium[2] and The Netherlands,[3] national plans – often based on intense multi-level negotiations by the full spectrum of governmental, semi-governmental, non-governmental and private entities – indeed aim to fundamentally change the national and, thus, the European energy system. In good Keynesian fashion, the economic downturn caused by the coronavirus pandemic seems to have only increased the billions of Euros assigned to the energy transition. Add trilateral co-operation between the regions[4] and the announcement of two international, privately-led R&D consortia aiming to scale up electrically-powered chemical plants,[5] and it might appear that the chemical sector is soon to be independent of oil and gas. This conclusion could not be further from the reality.

In countries that are home to a large chemical industry base, such as Belgium, Germany and The Netherlands, a mere focus on molecules and electrons used to supply process energy might lead to the wrong conclusion, as it neglects the physical reality of chemical processes that currently convert fossil resources into chemical products. In fact, seeing the current transition as just a transition in the energy sector

1 In Germany, the 'Climate Action Programme 2030' was published in late 2019. The programme contains a proposal for a new national carbon pricing system that covers the transportation and buildings sectors. In 2020, a 130 billion Corona economic stimulus package was announced that contains funds earmarked to take further steps in the energy transition, including a budget of 7 billion euro for the national hydrogen strategy and 2 billion euro for foreign trade partnerships related to this strategy.

2 In Belgium, the National Energy and Climate Plan 2021 – 2030, to which additional plans from the federated entities were annexed for further information, was published in 2019. It, amongst others, includes plans to invest in the electricity grid and natural gas infrastructure.

3 In the Netherlands, multi-stakeholder discussions and negotiations resulted in a national climate agreement, which sets out the pathway for the energy transition. To reach the set targets, amongst others, the Taskforce Infrastructuur Klimaatakkoord Industrie (TIKI) was commissioned to identify the infrastructural bottlenecks expected by the industry. An additional instrument to reach the reduction in the industry sector is a proposed levy on avoidable emissions.

4 The Trilateral Chemical Region, or 'TriLog', is an initiative by the three ministries for economic affairs in Flanders, the Netherlands and North Rhine Westphalia that started in 2017.

5 In the summer of 2020, Shell and Dow Chemical announced a joint development agreement to accelerate technology to electrify ethylene steam crackers. A year earlier, BASF, Borealis, BP, LyondellBasell, Sabic, and Total disclosed the formation of their 'Cracker of the future' consortium.

– or even more narrowly, as a transition in the electricity sector – would be as wrong as seeing it as the first energy transition in history.[6]

Apart from using energy to drive chemical processes, chemical reactions require hydrocarbons as material input. More specifically, energy carriers do not only provide steam, heat, and electricity, but they also supply the necessary carbon and hydrogen molecules to physically construct the desired products. The latter use of energy carriers is referred to as 'chemical feedstock use' or 'non-energetic use.' Overlooking this demand category is hard to justify, considering that chemical feedstocks typically account for more than half of the total inputs to the chemical sector. This sector, in turn, accounts for 14% of global primary oil demand and 8% of global primary gas demand, making it the largest industrial consumer of these fuels, according to International Energy Agency (IEA) data.[7] Cumulatively, from 1970 to 2018, the IEA data show that oil, natural gas and coal feedstocks have accounted for 74%, 25% and 1% of total feedstocks, respectively, and, thus, jointly for virtually all feedstocks.

The 'non-energetic use' demand category is relevant, as it shows the large amounts of fossil carbon atoms that are being embedded in chemical products. If these chemical products are incinerated after the use phase, these embedded carbon atoms enter the atmosphere in the form of CO_2 predominantly. In carbon accounting, direct emissions associated with a process are reported as scope 1 emissions. These emissions, such as those from combustion boilers, furnaces, or vehicles, occur from sources that are owned or controlled directly by chemical producers. Scope 2 emissions account for the emissions generated during production of purchased electricity. Scope 3 emissions fall under the control of a company, in the sense that it could potentially produce products with a lower carbon footprint, but the emissions occur from sources not owned or controlled by the company. This category includes the end-of-life emissions that are emitted after the use of chemical products.[8]

The level of value chain co-operation required to lower these emissions makes scope 3 greenhouse gas (GHG) emissions reduction challenging. Moreover, waste processing is currently not included in the EU Emissions Trading Scheme (ETS). Instead, it is covered by the EU's Effort Sharing Decision, which sets national emission reduction targets for 2030 for individual Member States ranging from 0% to -40%

6 For a history of energy transitions, see, e.g., Fouquet, R. (2010) 'The slow search for solutions: Lessons from historical energy transitions by sector and service' or CIEP (2014) 'Transition? What Transition?'

7 IEA (2018) 'The Future of Petrochemicals.'

8 For a more detailed description of scope 1, 2 and 3 emissions, see the GHG protocol.

from 2005 levels.[9] Chemical products are an eminent example of products that are traded internationally, tying scope 3 emission reductions of chemical companies to emissions directly induced by local waste management practices, and vice versa.

In this paper, we focus on the feedstock side of the carbon equation. This is done by first examining the emergence of the chemical industry in North-West Europe and then by studying what patterns can be distilled from earlier transitions that took place in the region. Based on these past patterns, insights into the dynamics and market forces that led to choices for certain feedstocks emerge. Additionally, the present-day chemical ecosystem in the ARRRA.[10] is described specifically in terms of refining, steam cracking and plastic production and the ways that these processes are interconnected. Finally, we contrast the observations made in this study with policy proposed in the contemporary energy discourse.

This effort builds on CIEP's previous work, including the publications 'Refinery 2050: Refining the clean molecule'[11] and 'Long-Term prospects for North-West European refining.'[12] In parallel, it sets the stage for continued research in this direction, providing handles for the evaluation of the medium-term prospect of alternative feedstocks.

9 See regulation 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013.

10 In this paper, the ARRRA includes the Belgium subclusters of The Port of Antwerp and the Campine industrial area, the Dutch subclusters of the Port of Rotterdam - Moerdijk industrial area, the Chemelot sites near Geleen and the industrial areas in the province of Zeeland, and the German subclusters of the Ruhr – Gelsenkirchen industrial area, the Rhine – Cologne industrial area (both in North Rhine-Westphalia) and the Ludwigshafen area (in Rhineland-Palatinate).

11 CIEP (2018) 'Refinery 2050: Refining the clean molecule.'

12 CIEP (2016) 'Long-Term prospects for North-West European refining.'

2 DESIGN BY EVOLUTION

The ARRRA chemical value chain is characterised by a myriad of compounds that can be feedstocks, intermediates, and final products in a highly interconnected system of chemical conversion plants, infrastructure, and storage facilities. Many of these plants create multiple compounds at the same time. Moreover, some plants are also capable of processing various feedstocks as substitutes, adding further complexity to the system. Despite these intricacies, the logic behind the current chemicals ecosystem can be explained by combining the technical lens of organic chemistry and process technology with the lenses of historic, (geo)economic and (geo)political developments. This multi-disciplinary toolbox helps to explain today's complex chemical (sub)clusters, as well as their basic configuration and interdependencies.

THE EMERGENCE OF AN INDUSTRY

By reflecting on how cards were played in the past, we can build a better understanding of the mechanisms and forces at play in the chemical industry today and in the future. This not only uncovers the linkages that make the chemical systems resilient and how these linkages changed in previous feedstock transitions, but it also helps clarify the current nature of the ARRRA's chemical industry. Let us, therefore, first look at how 'chemical manufacturing in Europe started'.

COAL ROOTS

Chemistry – or combining substances to (unknowingly) let them react – has been a practice throughout much of human history. A defining moment for the base chemicals production that we assess in this paper was the 1909 invention of Bakelite – the first commercially successful, synthetic organic compound or *plastic*.[13] Therefore, we use this moment to begin our retrospective.

In the early 20th century, organic chemistry revolved to large extent around coal tar, a by-product from coke production. Required for steelmaking, coke is produced by coal pyrolysis, yielding coal tar and coke gas (also known as 'town gas') as marketable by-products.[14] As coal tar is a mixture of various components, distilling it separates these into many useful products. First pursued for the synthetic production of dyes,

13 Patent number 942699, granted December 7, 1909 by the United States Patent Office to Leo H. Baekeland.
14 To understand how Europe transitioned from town gas to natural gas, see Gustafson (2020): The bridge, natural gas in a redivided Europe.

coal tar distillation yields phenol, one of the feedstocks in Bakelite production. Bakelite's electrical nonconductivity and heat-resistant properties made it an excellent material for construction of electric appliances, the most well-known of which were the Bakelite telephones. Such coal-based chemistry is referred to as *carbochemistry*. Since carbochemistry depends on coal coking plants for its feedstock, chemical plants were located close to coal mining locations or to waterways and railroads used for coal imports. In Belgium, chemical sites were situated in the coal region around the Meuse river, for example, and in the east around waterways near Antwerp and along the Brussels-Scheldt canal.[15] In the Netherlands, chemical sites were situated in the coal region in Limburg (Maastricht and Treebeek).[16] In Germany, chemical production clusters were located in the coal region around the Rhine-Ruhr rivers. One such cluster is in Ludwigshafen, where a coal gas plant owner in Mannheim set up a chemical plant on the opposite side of the Rhine river.[17] In these patterns, a clustering of industries has already emerged, and the foundations of some of today's chemical clusters can still be traced back to this era of carbochemistry.

OIL-BASED EXPANSION

Shortly after the Second World War, when carbochemistry was still dominant, a gradual shift to oil-(petroleum-) based chemistry began, heralding the age of *petrochemistry*. In Europe, post-war reconstruction efforts required mainly heavier oil products, such as diesel and fuel oil, while demand for lighter oil products, such as gasoline, was lower compared, for example, to that in the United States. This resulted in a high availability of naphtha, a by-product of oil refining[18] that the chemical sector could benefit from as feedstock. In Germany, the expertise and assets built for fossil-based synthetic fuel production and processing were situated favourably for experimenting with petrochemical production methods and feedstocks on a commercial scale.[19] In parallel, technological developments increased the capacity of newly built steam crackers,[20] and consumer interest in and demand for new plastic products were high. As a result, a naphtha steam cracker construction

15 The Belgian Chemical Industry, Board of Economic Warfare, 1943.
16 De la Bruhezè, A.A.A., Lintsen, H.W., Rip, A., Schot, J.W., 'Techniek in Nederland in de twintigste eeuw,' (2000) Deel 2 Delfstoffen, energie, chemie.
17 BASF History 1865-2015, 2015.
18 Naphtha is a broad term referring to a mixture of acyclic and cyclic hydrocarbons with 5 to 12 carbon atoms. In addition to its use as steam cracker feedstock, this light distillate is used for gasoline blending.
19 Boon M. (2014) Oil Pipelines, Politics and International Business, p. 89.
20 In a steam cracker, feedstocks such as naphtha, LPG and ethane are 'cracked' into organic base chemicals required for plastic production. See Section 3 for a more detailed description.

wave emerged during the 1960s and the first half of 1970s, rapidly expanding total production capacity in the region.[21]

For a brief period, carbo- and petrochemistry coexisted, but in the 1960s, petrochemistry outcompeted carbochemistry and oil became the bulk feedstock for chemical production in the ARRRA region. To illustrate this, even in Germany, where the carbochemistry sector was traditionally strong, producers switched to petrochemical production methods, and, by 1963, the share of coal as chemicals feedstock declined to 37%.[22] Naphtha steam crackers were built, in part, by existing chemical companies at their carbochemistry sites, such as the Dutch State Mines at Geleen (1961) and BASF in Ludwigshafen (1965). However, the transition from coal to petroleum also presented opportunities for market entry by new industrial players (helped by a weakened German chemical sector after the war). As new entrants lacked legacy production sites and were seeking good access to the new feedstock, new production locations also developed. Steam crackers were built in the Antwerp (by Petrofina in 1964) and Rotterdam (by Shell in 1967) harbours, where oil refineries were already in operation, and along the Scheldt estuary in Terneuzen (by Dow Chemical in 1972). While with carbochemistry there was a stronger link between feedstock production (i.e., coal mining) and chemical plants, the shift to petrochemistry also (partially) moved feedstock production (i.e., oil production) farther away from the chemical clusters. Even though, over time, multiple assets have changed ownership (and names) via mergers and acquisitions, the contours of the chemical clusters in the ARRRA, which were laid in the transition towards petrochemistry, are still in place today.

NATURAL GAS LIQUIDS COMPETITION

In addition to naphtha, steam crackers can be configured to take in a share of natural gas liquids (NGLs), such as ethane, propane or butanes, as feedstock either along with or instead of naphtha.[23] This encompasses the subset of liquefied petroleum gas (LPG), which consists of propane, butane and isobutane. Historically, unless production was close to demand centres, the infrastructure costs involved in bringing NGLs to market were too high to be commercially attractive and often led

21 De la Bruhezè, A.A.A., Lintsen, H.W., Rip, A., Schot, J.W., 'Techniek in Nederland in de twintigste eeuw,' (2000) Deel 2 Delfstoffen, energie, chemie, tabel 7.1.

22 Geschiedenis van de Koninklijke Shell, Deel 2 – H.5 'De regenboog achterna.'

23 Natural gas liquids (NGLs) are a group of hydrocarbons including ethane, propane, normal butane, isobutane, and natural gasoline. NGLs can be separated from natural gas in a natural gas processing plant. Where this is technically and economically feasible, up to some amount, ethane can also be left in the natural gas stream. In addition, NGLs production is related oil production and processing as NGLs are obtained from associated (petroleum) gas and refinery gasses, respectively.

to these streams being flared or vented as stranded by-products. The establishment of a petrochemical industry in the Middle East around the 1980s enabled the monetization of NGLs by allowing ethane-based chemical plants in the region to benefit from very low feedstock prices. This dynamic repeated itself more recently following the shale revolution in the United States.[24] As high quantities of NGLs are yielded in both shale oil and shale gas production, large volumes became available in the US after 2009.[25] To exploit the subsequent low NGL prices, this led to the reconfiguration of US steam crackers from naphtha to ethane feedstock and the construction of numerous new ethane-based steam crackers, as well as NGLs export terminals.

The effects of this NGLs-fed resurgence of the US chemical industry were felt globally.[26] The addition of new low-cost production capacity changed the merit order of chemical producers, after which the downward price pressure spread globally via international markets. In the ARRRA cluster, the effect became apparent through a widening propane-naphtha price spread. Exports of NGLs in the form of LPG and ethane became more interesting for NGLs producers to escape the glut and low prices, while it was also an interesting feedstock for chemical producers to exploit.[27] In part, these feedstocks were taken up in the existing steam cracker capacity (Figure 1). As access to harbour terminals is crucial to NGL imports, either by a coastal location or by access to a pipeline with a terminal connection, this development changed the playing field for steam crackers. For the first time in more than two decades, a new steam cracker (ethane-fed) is under construction in Antwerp, set to be operational by 2025.[28] With this partial feedstock transition to NGLs, locally sourced feedstocks were again replaced by feedstocks produced outside the ARRRA chemical cluster.

24 CIEP (2013) 'US Refining dynamics', p 32.

25 In the decades leading up to 2008, NGLs field production in the United States averaged around 1.7 million barrels per day (MB/D). From 2009 to 2019, NGLs production accelerated from 1.9 MB/D to 4.8 M/D. Data source US Energy Information Agency.

26 The Oxford Institute for Energy Studies (2014) 'US NGLs production and steam cracker substitution.'

27 As ethane has a boiling point of -89 °C, even lower compared to LPG, ethane shipping is difficult and has historically seen little use. Following the shale boom, new ethane shipping options have been pursued; the most prominent efforts are by INEOS. By operating a fleet of purpose ordered and built ethane carriers, INEOS operates a 'virtual pipeline' for ethane from the US to Europe.

28 The INEOS 'Project ONE' includes a steam cracker with a 1-1.25 million t/yr capacity that is intended to be supplied by the fleet of ethane carriers.

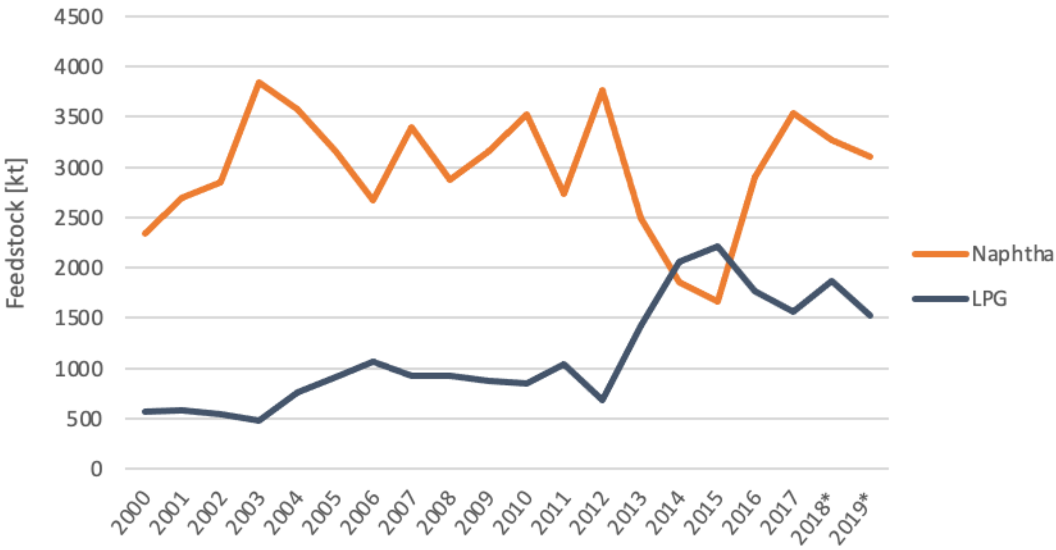


FIGURE 1 – PETROCHEMICAL FEEDSTOCK CONSUMPTION IN THE NETHERLANDS.

* PRELIMINARY DATA

SOURCE: CENTRAAL BUREAU VOOR DE STATISTIEK, 'AARDOLIEPRODUCTENBALANS'

As the price spread between propane and naphtha in North-West Europe widened, it negatively impacted the competitiveness of local (naphtha-based) steam crackers. Subsequently, around 2013, a gradual disintegration of the ARRRA cluster was regarded as a plausible future scenario.[29,30] However, such a scenario, with a vicious circle of fragmentation, did not materialise. When naphtha prices declined again following the collapse of the oil price in 2014, the propane-naphtha price spread narrowed, and further deterioration of the competitiveness of European steam crackers was averted. By the end of the 2010s, the ARRRA cluster absorbed levels of NGLs that were higher than those at the start of the decade, though not as high as the projections made back in 2013. With a partial feedstock shift to NGLs, the ARRRA again showed resilience to feedstock changes. Looking forward, with the backdrop of increasing pressure to lower emissions, the question arises as to which forces added to this resilience.

29 Deloitte (2013) 'The shale gas revolution and its impact on the chemical industry in the Netherlands.'

30 Industrielinqs (2013) 'Kamp presenteert actieplan voor Nederlandse chemie.'

BOX 1 – FEEDSTOCK OPTIONALITY DURING THE COVID-19 PANDEMIC.

The ARRRA chemical cluster, as well as clusters in Asia that use naphtha as their main feedstock, benefit from competitively priced naphtha. In contrast, clusters in the Middle East and the United States thrive in price environments with competitive NGLs and higher-priced naphtha. While international markets dictate that disintegration scenarios for naphtha-based clusters could return if oil prices rise, the current low oil price environment gives limited room for such thinking.

In 2020, the covid-19 pandemic created market conditions in which naphtha traded below propane.[31] This made naphtha an increasingly favourable option for steam crackers that have the ability to adjust their feedstock intake. Crackers are, however, not solely focused on sourcing competitive feedstock, but aim to optimise their margins by maximising the difference in feedstock costs and the value of the corresponding product slate. Compared to propane, naphtha yields a more diverse slate of products, including a higher share of heavier products. Similar to feedstock markets, the markets for chemical products were destabilised as the result of the pandemic, making finding the optimum feedstock-product balance difficult. As crackers also had to consider refinery shutdowns as a result of a disappearing fuel demand, guaranteeing continued operation was challenging.

While a switching propane-naphtha spread showed the benefit of feedstock optionality and is generally positive for naphtha-based crackers in Europe, future investment decisions are guided by projections of longer-term price-cost structures and an asset's position in a wider portfolio.

FORCES SHAPING THE INDUSTRY

From the discussion on how the chemical industry transitioned from coal to oil and gas derivatives, it becomes clear that while feedstock production moved increasingly farther away from the ARRRA, chemical clusters have thus far showed resilience. Despite feedstock transitions and a changing global playing field, chemical products in North-West Europe are still being produced at sites that were associated with coal mining over a century ago. This cannot be explained solely by regarding investments in steam crackers as sunk costs, as parties have kept investing and expanding their assets. Also, over time, new production capacity and capabilities were continually added at or close to the same sites. This indicates that there are a number of additional factors at play that provide the existing cluster and integrated sites with additional benefits.

31 Argus (2020) 'North-West European LPG prices plummet.'

CLUSTERING FORCES

Production of ethylene generally causes a forward and backward clustering of the production chain.[32,33] Being gaseous under normal conditions, ethylene transportation is difficult, so production and take-off tend to be located close to each other (forward clustering). By-products created in steam crackers are used, in part, to provide process energy for the steam cracker itself, but also as feedstock sent back to refineries (backward clustering) and for the production of other chemical products. Other technical arguments for clustering include optimization via heat integration and the shared use of infrastructure, waste management facilities, maintenance services, and common process technology. While this technical lens offers strong arguments, a wider view also shows clustering forces from other perspectives.

Introduced in a paradigm-shifting publication, Michael Porter's theory of clusters and clustering forces provides a broader explanation.[34] According to Porter (1998), the contemporary economic map of the world was dominated by what he calls clusters: geographic concentrations of unusual competitive industries in particular fields. Porter's clusters encompass an array of linked industries and other entities important to competition. They include, for example, suppliers of specialized inputs, such as components, machinery, and services, and providers of specialized infrastructure. Clusters also often extend downstream to distribution channels and customers, laterally to manufacturers of complementary products, and to companies in industries related by skills, technologies, or common inputs. Finally, many clusters include governmental and other institutions – such as universities, standards-setting agencies, think tanks, vocational training providers, and trade associations – that provide specialized training, education, information, research, and technical support.[35]

Building on his earlier work, Porter presents clusters as an operationalization of factors that he includes in the 'diamond of national advantage.'[36] In this diamond, technical advantages of clustering are complemented by factors created by economic, social, and governmental dynamics. As part of his theory, Porter promotes the idea that nucleation of most clusters is independent of government action – and

32 Ethylene is one of the most widely produced organic base chemical and is the main steam cracker product. See Section 3, Chemical conversion and plastic production, for a more detailed description.

33 As noted by Molle and Wever (1984), 'Oil Refineries', 427-428.

34 Porter, M. (1998) 'Clusters and the New Economics of Competition,' Harvard Business Review.

35 In both the technical and more institutional views, clustering can be seen as a form of self-organisation. In complex systems theory, self-organisation is a process whereby some form of overall order arises from local interactions between parts of an initially disordered system.

36 Porter, M. (1990) 'The Competitive Advantage of Nations,' Harvard Business Review.

sometimes despite it. However, in his view, as well as in that of many of his contemporaries, where clustering occurs, governments can and should promote further formation and upgrading and develop public or quasi-public goods that have a facilitative function for many linked businesses.

GOVERNMENTAL FORCES

While the idea that firms and associated entities form clusters stands strong, Porter's notion that clusters often nucleate independently of government action is less universally accepted. In fact, the history of the ARRRA chemical cluster shows strong governmental influences.

It was political scientist Charles Tilly who coined the phrase 'war made the state and the state made war.'[37] This aphorism also applies to Europe, where it is clear that strategic interests and war have profoundly impacted and shaped development. In the first half of the 20th century, the industrial regions in North-West Europe (including the ARRRA) played an important role in state building. This includes the chemicals sector, as the production capabilities of fuel, lubricants, and propellants, among others, were stimulated in a context of strategic positioning of states. Many of the key industrial breakthroughs during this era were subject to substantial state stimulus. For example, government-supported research institutes carried out important carbochemistry research and development.[38] During the 1930s and 1940s, as well as in the period immediately following the Second World War, many companies and plants contributed to nations' military capabilities. After the war, the Allies, the US in particular, sought to break the power of German industry by forcing Germany to open up its market and stimulate competition by dismantling and decartelising the coal, steel, and chemical sectors.[39]

Apart from strategic positioning, governments also exerted influence on industry for employment, environmental, or other (on a regional development scale) reasons. For example, with the managed closure of the coal mines operated by Dutch State Mines in Limburg, part of the deal was that the same company would invest (with government backing) in an expansion of its (petro)chemicals production branch in Limburg to compensate the region for the lost mining activities and to maintain employment opportunities.[40] This included government's facilitation of pipeline

37 Tilly, C. (1975) 'The formation of National states in Western Europe,' Princeton University Press, p.42.

38 A prominent example of this is the invention of the Fischer-Tropsch process during the interbellum, named after its inventors, who were working at the publicly funded Kaiser Wilhelm Institute for Coal Research. Later, this process was applied to negate the access to crude oil resources for the provision of liquid fuels.

39 Boon, M. (2014) 'Oil Pipelines,' *Politics and International Business*.

40 Speech, Joop den Uyl (then functioning as Minister of Economic Affairs), 17 December 1965.

corridor connections for feedstock transport from the oil refineries in the Rotterdam area to (German) customers for product transport. As American scholars Fred Block and Matthew Keller make clear, in the second part of the twentieth century as well, it has not always been Adam Smith's invisible hand, but also the hand of governments, that have proven decisive in some economic development.[41] They argue that historical experience with the innovation economy provides powerful arguments against the core assumptions of 'market fundamentalism.' They use the development of the plant-based, biodegradable plastic polylactic acid (PLA) as an example to illustrate that the role of governments (the US in this example) in radical technological innovations goes much further than correcting market failure.[42] Government-sponsored technological innovations can, in fact, create entire markets out of nothing.

To this day, the idea that the government, in the most successful economies, has gone beyond creating the infrastructure and setting the right rules is no longer confined to the books of popular economists.[43] It has found its way into many policy documents, ranging from the European level to the municipal level.[44]

COMPETITIVE FORCES

In commercial but regulated markets, competition complements the governmental and clustering forces described above. The petrochemical sector, as with every sector, has an underlying structure – or a set of fundamental economic and technical characteristics – that gives rise to this state of competition. One way to conceptualise these fundamentals is given by Michael Porter's five forces model (Figure 2).[45] In this model, actors are not only 'jockeying for position' mutually, but are also subject to competition from external actors: suppliers, customers, potential entrants, and substitute products.

Being a mature industry in bulk goods, characterized by high fixed costs, large incremental capacity additions and, particularly in Europe, slow demand growth, margins are low and competition between chemical producers is fierce. Further

41 Block, F. and Keller, M.R. (2016) 'State of innovation,' p.3.

42 Starting in 1995, the US government funded the 'Advanced Technology Program,' designed to stimulate early-stage advanced technology development, co-financed research on a project undertaken by a Cargill and Dow Chemicals alliance. By 1999, the project had led to a proprietary PLA polymer, which is degradable under specific conditions, and the production of which uses 30 to 50 percent less energy. By 2007, the project company (NatureWorks) had become the largest U.S. commercial producer of bioplastics.

43 E.g. Mazzucato, M. (2011) 'The Entrepreneurial State', Anthem Press.

44 See, for example, Mazzucato, M. (2018) 'Mission-Oriented Research & Innovation in the European Union' and Provincie Limburg (2020) 'Informerend stuk Limburgse Waterstofagenda.'

45 Porter, M. (1973) 'How Competitive Forces Shape Strategy', Harvard Business Review.

complicating this is the existence of high exit barriers, which may keep actors operating despite low or even negative returns.[46] The relationships between chemical producers and their suppliers are complex and diverse. Some petrochemical producers are dependent on their feedstock providers – currently, oil refiners or gas processers – that can exert bargaining power. In a number of cases, chemical companies and their supplier(s) are vertically integrated in a single company (e.g., oil-producing and refining companies with petrochemicals divisions). Moreover, there are high switching costs, including sunk costs of infrastructure investments and credible – and, in recent decades, regularly executed – threats of forward and backward integration.

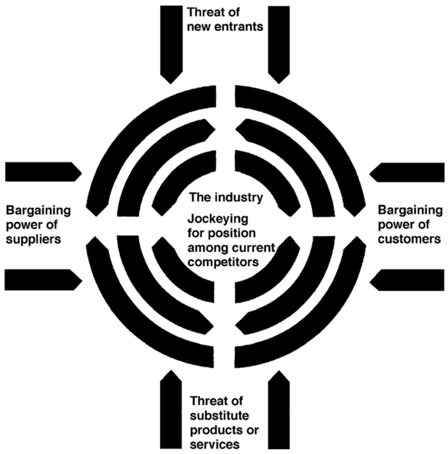


FIGURE 2 – FIVE FORCES GOVERNING COMPETITION IN AN INDUSTRY.

SOURCE: HOW COMPETITIVE FORCES SHAPE STRATEGY, M. PORTER, HARVARD BUSINESS REVIEW.

The bargaining power of suppliers is partly mitigated by the optionality that chemical producers have in substituting between naphtha and NGLs feedstocks. On the customer side, large-volume sales of generally undifferentiated products priced on international markets create a strong bargaining position for clients of chemical producers. The industry's high capital requirements and, within the ARRRA, engrained infrastructure and saturated market make for a difficult environment for new entrants to succeed.[47] However, new international entrants in the US, the Middle East, Russia and China, supported by local governments to varying degrees,

46 With dynamics that are similar to those in the chemical industry, the main barriers to exit in crude oil refining and their role in past refinery restructuring cases is explained in CIEP (2016) Long-Term Prospects for North-West European Refining.

47 Illustrating this is the fact that the Ineos 'Project ONE' steam cracker to be built in Antwerp is the first new steam cracker in Europe in decades; market commentators have noted that it is 'surprising' and that 'Europe has long been languishing at the bottom of the most-ripe-for-investments list.'

do pose a serious threat (see Box 2). From a competition perspective, substitute products limit the potential of an industry by placing a ceiling on the prices it can charge.[48] In a world driven solely by competitive forces, product substitution would be driven by the price-performance trade-off offered by substitute products. In industrial clusters such as the ARRRA, however, the clustering and governmental forces add to the factors that make participants design their product portfolio and, thus, to how the industry evolves.

BOX 2 – THE ARRRA VIS-À-VIS THE WORLD; GROWTH UBIQUITOUS, VARYING APPROACHES TO GOVERNMENT INVOLVEMENT.

Once the largest region for chemical production, a mature market, a stable population and a lack of resources have led to a decline in Europe's share in base chemical production. While a rare occurrence in Europe, new steam crackers are coming online regularly in the US, Russia, the Middle East, and China. Evaluating industry development plans in clusters outside Europe shows the monetisation of competitive local resources as a recurring motive. The role that national governments and market forces play varies by region. Recently, the COVID-19 crisis and subsequent depressed market conditions deeply affected investment plans globally. In the short term though, ongoing work on construction sites around the world directed by earlier investment decisions and existing policies will lead to production capacity growth.

In the US, the petrochemical industry invested heavily to capitalise on the abundant, low-cost NGL feedstocks that emerged from the shale oil and gas revolution. In the last four years, eight new crackers and a wave of polyolefins plants have begun operations or are in the process of starting up, and even more are planned for start-up throughout the 2020s.[49] In addition, a new ethylene export terminal started operations in late 2019.[50] With these expansions, the US is set to complement its position as top exporter of refined oil products with an increasingly important role as exporter of feedstocks, intermediates and chemical products. Whether the sector is able to live up to these expectations also depends on demand growth, which is currently affected by tariffs as a result of the US-China trade war.

48 An analogy from the refining industry is the price ceiling that naphtha forms for natural gas liquids. An example from the plastics industry is customers choosing cheaper virgin plastics over recycled plastics.
49 ICIS (2019) Global Chemicals outlook 2020.
50 S&P Global Platts (2019) Enterprise to ship 1st cargo from new US ethylene export terminal this week.

In Russia, the petrochemical industry benefits from the relative proximity of hydrocarbon production areas and the country's vast oil and gas reserves. In the midst of the 2010s, the Russian Federation set out a plan to reduce the dependency of the Russian economy on imported intermediates and chemical products, while increasing domestic demand for locally-made chemical products.[51,52] In six chemical clusters, capacity expansions, infrastructure investments, and accommodation of engineering, machine-building and service companies should lead to more-integrated and competitive production. These plans cannot be seen in isolation from Russia's downstream oil industry, which, in the last two decades, has been shaped predominantly by federal tax policy.[53,54] Export taxes were introduced as a means to keep refined product prices low for domestic consumers and to avoid shortages, but they had serious spillover effects. A mechanism, referred to by some as refining 'subsidies,' enabled Russian refiners to source crude at great discounts, and this artificial incentive led to increased domestic refining levels and boosted the export of refined products.[55] In the latest increment in a series of tax reforms – the so-called 'tax manoeuvres', the Federation aims to correct these mechanisms and find a balance between supporting the industry and reforming it by demoting refining operations that are not financially sustainable. It plans to gradually phase out export taxes on crude oil and refined products and to replace them with excise tax refunds on refined products. Market players in the Russian chemical industry now hope to benefit from these excise tax refunds.[56,57]

As only a minority of the crude produced in the Middle East is refined locally, increasing local petrochemical capacity is seen as an area for potential growth and economic diversification, and as a way to better monetise hydrocarbon reserves. The region uses NGLs mainly in chemical production, while the bulk of naphtha that is co-produced in its refineries is exported. In the past decades, governments of resource-holding countries frequently flagged investing in petrochemicals as a key priority in their visions for the future, as they did in their

51 Garant (2016) Development strategy of the chemical and petrochemical complex for the period up to 2030.
52 An example of Russia's push towards petrochemicals is the ZapSibNefteKhim plant in western Siberia that uses LPG as feedstock and that is operating at full capacity since December 2020. See Reuters (2020) UPDATE 1-Russia's Sibur ramps up ZapSibNefteKhim plant to full capacity and Petroleum Economist (2020) Russia embarks on petchems push.
53 Clingendael International Energy Programme (2015) Russia's oil export strategy: Two markets, two faces.
54 The Oxford Institute for Energy Studies (2019) Russia's heavy fuel oil exports: challenges and changing rules abroad and at home.
55 Ibid.
56 BNE Intellinews (2020) Russian petrochemical sector on tenterhooks as government debating "negative export duties."
57 Creaon Group (2020) Russian LPG market hopes for reverse excise tax

latest editions.[58] Investments were especially strong in the 2000s, when oil and gas prices were rising in tandem and demand in China was growing steadily. The pro-cyclical nature of investment in the industry showed in the years following the crude oil crashes in 2008 and 2014 by lower capacity additions. As for the long term, the ambition to utilise hydrocarbon reserves is still – or, perhaps, more clearly – on the table, as governments and major national oil companies in the region are increasingly looking to crude-oil-to-chemical (COTC) projects. This technology allows the direct conversion of crude oil to base chemicals and could increase the percentage of the barrel that is used to produce chemicals from the conventional 10–15% to the 40%– 60% or even the 80% range.[59] In late 2020, though, the region's largest and most developed COTC plan, a USD 20 billion plant at Yanbu on Saudi Arabia's Red Sea coast, was shelved, as the joint-venture companies aimed to preserve cash and look at integrating existing facilities instead.[60]

China differs from the US, Russia and the Middle East in that it is not a major oil and gas producer but a net-importer.[61] Just like North-West Europe, South Korea, Japan, and Taiwan, the country depends on imports of crude and petrochemical feedstock to meet demand for its large and growing number of chemical plants. China's reliance on a small group of supplying countries for the bulk of its crude imports puts pressure on Chinese policy makers to find alternatives for improving the security of the country's (oil) supply.[62,63] For the petrochemical sector, decisions makers might have felt a similar pressure. At the start of the previous decade, petrochemical producers in China built numerous coal-to-olefins (CTO) and methanol-to-olefins (MTO) plants to leverage the country's vast coal deposits and to provide work in more-remote provinces with coal reserves. As the competitiveness of these plants is challenged in the current price environment, and given the high process emissions of the technologies, the commissioning of new CTO and MTO plants seems unlikely. A development that is expected to

58 The Government of Abu Dhabi (2008), The Abu Dhabi Economic Vision 2030; General Secretariat For Development Planning (2008) Qatar National Vision 2030.; Kingdom of Saudi Arabia (2017) Vision 2030.

59 Chemical Week (2019) Crude oil–to–chemicals: A game changer for the chemical industry.

60 Reuters (2020) Saudi Aramco and SABIC reassess crude-oil-to-chemicals project.

61 In fact, China became the largest importer of crude oil in 2017 and the largest importer of natural gas in 2018: US Energy Information Agency (2018), 'China surpassed the United States as the world's largest crude oil importer in 2017'; US Energy information Agency (2018) China becomes world's largest natural gas importer, overtaking Japan.

62 IHS Markit (2018) Crude oil-to-chemicals projects presage a new era in global petrochemical industry.

63 In addition to high external dependency, a low marketisation level remains a defining characteristic for China's petroleum industry, amongst others, expressed by strict controls on oil imports and state-owned enterprises that dominate the market. See, e.g., Chen S., Zhang Q., Mclellan B, Zhang T. (2020) 'Review on the petroleum market in China: history, challenges and prospects,' Petroleum Science.

change the Chinese chemical landscape is the construction of COTO plants that lead to a 'backwards integration' of chemical production plants into refineries. This technology can help make China less reliant on chemical imports. This trend can be well observed in the para-xylene (PX) value chain. According to market analysts, China had a PX deficit of 11 million tons per year in 2017, a gap that was filled by imports from Korea, Japan, and Taiwan.[64] New COTC plants are expected to decrease PX imports or even make China self-sufficient in PX, limiting market access for current suppliers and starting discussions on whether the same could happen in for other chemical compounds.[65,66]

RECURRING PATTERNS IN A CENTURY OF INDUSTRY EVOLUTION

Over the course of little more than a century, the chemical industry in the ARRRA evolved from using by-products from steelmaking to using oil-based and, later, NGLs feedstocks, along with profoundly increasing its output. Although the more recent competition from NGLs-based steam cracking has not led to a feedstock transition as complete as the earlier switch from carbo- to petrochemistry, parallels can be drawn between the two transitions.

First, while (upstream) parts of the value chain disappeared, clustering of chemical companies showed resilience to the feedstock changes. Petrochemical products are still being produced at sites that were traditionally associated with coal mining and coke production over a century ago. This resilience can be explained from a purely technical perspective, by arguing that steam cracker feedstocks are costly to source from a distance, and their gaseous products are best converted to products in proximity of the cracker. A perspective that widens the lens a bit further argues that clusters encompass a broader set of institutions that make critical masses that flock –and stick – together in one location. An element that is included in both explanations is the importance of infrastructural links. Specifically, pipeline access is vital to the competitiveness of sub-clusters that were deemed at risk, giving sites with competitive access to the alternative feedstock the upper hand.

Second, while governments have an important role to play in the development of infrastructure, their role is not limited to providing the right conditions to enable transitions to take place. Government involvement is most well-known and visible in

64 IHS Markit (2018) Crude oil-to-chemicals projects presage a new era in global petrochemical industry.
65 Ibid.
66 ICIS (2020) China's long-term ambition for paraxylene self-sufficiency seems close to being realized.

the energy sector, where it is wide-ranging and deep.[67] As seen in earlier feedstock transitions, governments have played important facilitating, as well as shaping, roles in the chemical sector. Governments have provided substantial and long-term support to new technologies and have created a framework for value chains to develop. This support has varied from granting licenses to process resources, to building and maintaining infrastructure, to providing support for research and development and early-phase investments. This does not mean that the petrochemical industry developed independently from markets. On the contrary, players in the petrochemical arena are not only 'jockeying for position' amongst themselves, but are also subject to competition from external actors, including suppliers, customers, potential entrants, and substitute products.

Finally, and maybe most importantly, the choices in feedstocks for the chemical industry cannot be seen in isolation from the surrounding industries and market conditions. Carbochemistry was built upon a by-product of coke and town gas production. Naphtha availability in the ARRRA during the 1950s and 1960s was created by a vast demand for heavier distillates in refineries and the expansion of market-based refineries, spurred by the mobility and heating sector. The high value of these products kept refineries producing, even as refinery product slates could not be skewed sufficiently to avoid an oversupply of naphtha as a by-product. Likewise, the shale pioneers were not seeking a new feedstock for plastic. They were drilling for oil or natural gas, resources of which the high value is predominantly created in sectors other than chemicals. While it is not uncommon for supply chains to serve multiple sectors, the chemical sector has proven particularly successful in seizing the feedstock opportunities created by companies seeking value in other sectors. This also implies that the chemical industry did not have to carry the full costs of setting up the supply systems for these feedstocks.

What does the ecosystem that emerged from the forces discussed in this chapter look like today? That is the question for the next chapter.

67 See CIEP (2014) 'Transition? What transition?' and CIEP (2019) 'From an invisible to a more visible hand?'

3 ARRRA'S CHEMICAL ECOSYSTEM

Depending on one's perspective, the organic chemical industry in the ARRRA can be regarded as a collection of subclusters or as one large supercluster created through high levels of interconnectivity between the subclusters. In both cases, there are a few crucial assets – refineries and base chemical production sites – feeding more-diverse chemical conversion plants and sites, all internally interconnected and with downstream operations via pipelines, railways and waterways (Figure 3). Within North-West Europe, the geographic distribution of refineries, base chemical production sites and chemical conversion plants is heavily skewed to the ARRRA.[68]

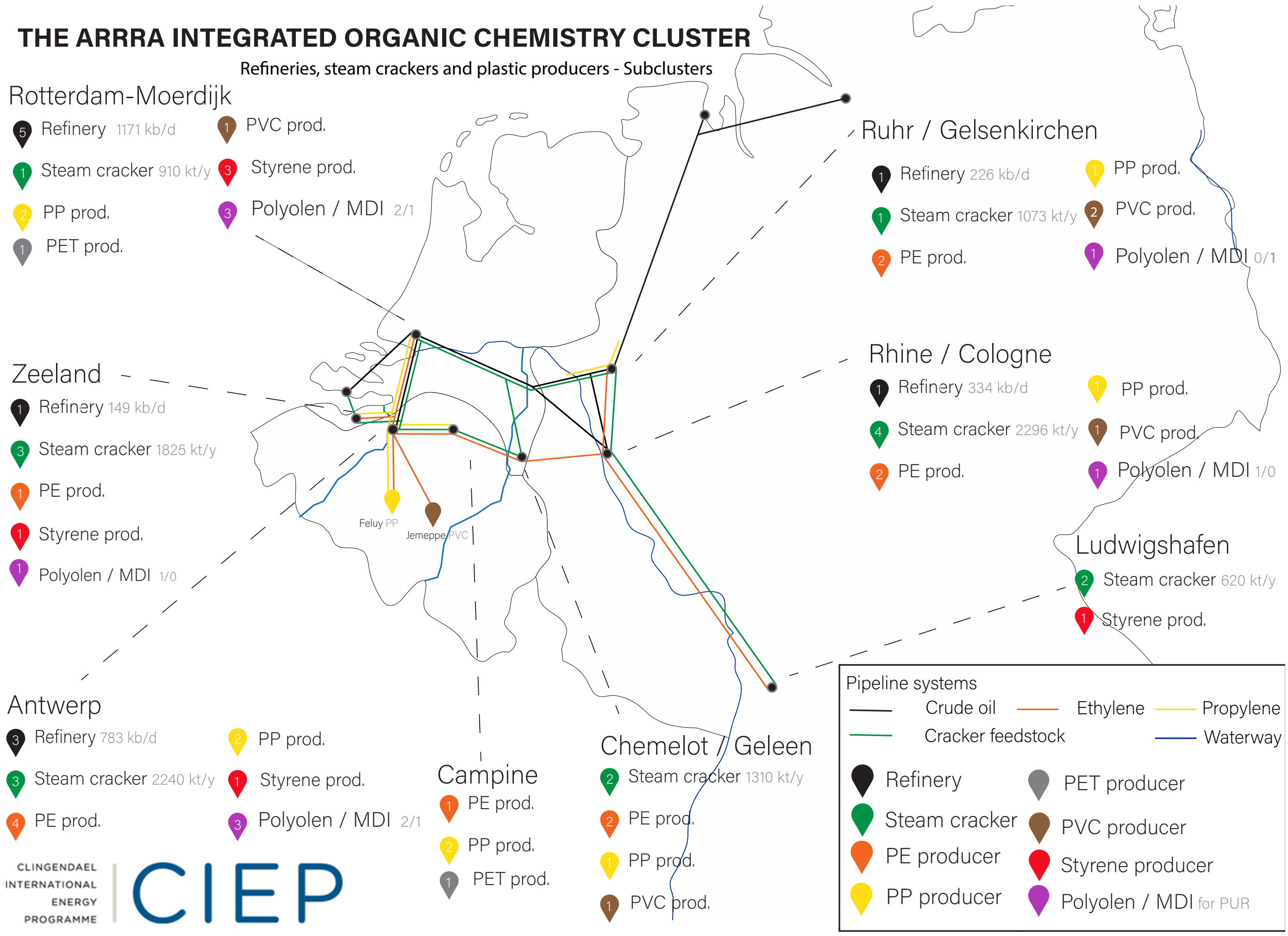


FIGURE 3 – REFINERIES, STEAM CRACKERS AND PLASTIC PRODUCERS IN THE ANTWERP ROTTERDAM RHINE RUHR AREA. ORDERED PER SUBCLUSTER AND INCLUDING PIPELINE AND WATERWAY INTERLINKAGES.

CIEP-ANALYSIS BASED ON VARIOUS SOURCES INCLUDING CRACKER CAPACITY BY PETROCHEMICALS EUROPE.

68 For an overview of the chemical industry landscape in all of Europe, see, e.g., maps by Petrochemicals Europe.

THE HYDROCARBON MOLECULE FROM PORT TO PLASTIC

In this paper, we describe the ARRRA's chemical ecosystem – specifically, refining, steam cracking and plastic production, and the ways in which these processing steps are interconnected. This paper does not aim to provide an exhaustive (technical) representation of production capacities for the entire portfolio of chemical products;[69] instead, it uses plastics – the largest category of chemical products – to illuminate interdependencies in the cluster and, thus, provide a basis for reflection on the institutional design of the 'Trilateral strategy for the Chemical industry.' In an industry that generally lacks availability of public data, this mostly qualitative approach provides a system perspective on the relevant level of aggregation.

BOX 3 – FILLING AND EMBRACING THE CHEMICALS DATA GAP

This study provides a mostly qualitative description of the ARRRA chemical ecosystem, as quantitative public data on the production, trade and use of chemical compounds in the ARRRA cluster are scarce. Understanding possible future feedstock transitions would benefit from the establishment of a factual foundation that gives quantitative insight into the production, trade and use of chemical products. Hence, this study joins a growing body of work calling for improved feedstock statistics.[70] Furthermore, it suggests that feedstock statistics initiatives should not be confined to national borders, but should also consider the relevant higher aggregation levels. For the chemical industry, this would be the ARRRA cluster.

While the chemical sector can evidently benefit from improved statistics, this will not lead to a comprehensive understanding of the chemical ecosystem. Given the complex and dynamic nature of the sector, a certain degree of uncertainty will persist no matter the efforts to collect statistics. Policy makers faced with this uncertainty should focus on developing adaptive policies that embrace uncertainty and are robust in a wide range of possible scenarios.

69 While representing a major component, plastics do not present the ARRRA's full portfolio of chemical products. In addition to various forms of adhesive, coatings, inks, detergents, glues, engine coolants, textiles and rubbers, this portfolio also contains methanol derivatives, including formaldehyde and fuel-blending components such as methyl tert-butyl ether (MTBE). Besides organic chemistry, inorganic chemistry is also performed in North-West Europe. At various sites, ammonia is produced via the Haber-Bosch process, mainly for application in fertilizers.

70 See, e.g., Ecoyfys & Berenschot (2018) 'Chemistry for Climate: Acting on the need for speed' or PBL (2010) 'Op weg naar een robuuste monitoring van de circulaire economie.'

CRUDE OIL REFINING AND NATURAL GAS PROCESSING

Due to the dynamics described in the previous chapter, transforming crude oil into useful fractions within the ARRRA cluster takes place in port areas and in regions with a history of coal production and carbon chemistry. Oil refineries produce a slate of very diverse products, with the exact composition and distribution between products depending on, amongst others, crude oil quality and refinery setup (Figure 4). Most relevant for the chemicals sector are naphtha and LPG production, though LPG is produced by refineries in smaller volumes than naphtha is. The ARRRA cluster has a combined refining capacity of approximately 2713 thousand barrels per day (kb/d). Five refineries – representing 1171 kb/d – are located in the Port of Rotterdam, and three refineries – 783 kb/d – are located in the Port of Antwerp.[71] Additionally, Gelsenkirchen, Cologne and Zeeland each have one refinery representing 266 kb/d, 344 kb/d and 149 kb/d, respectively.[72] NGLs are also produced in natural gas processing plants. For imported naphtha and NGLs, these production and processing steps take place in the country of origin.

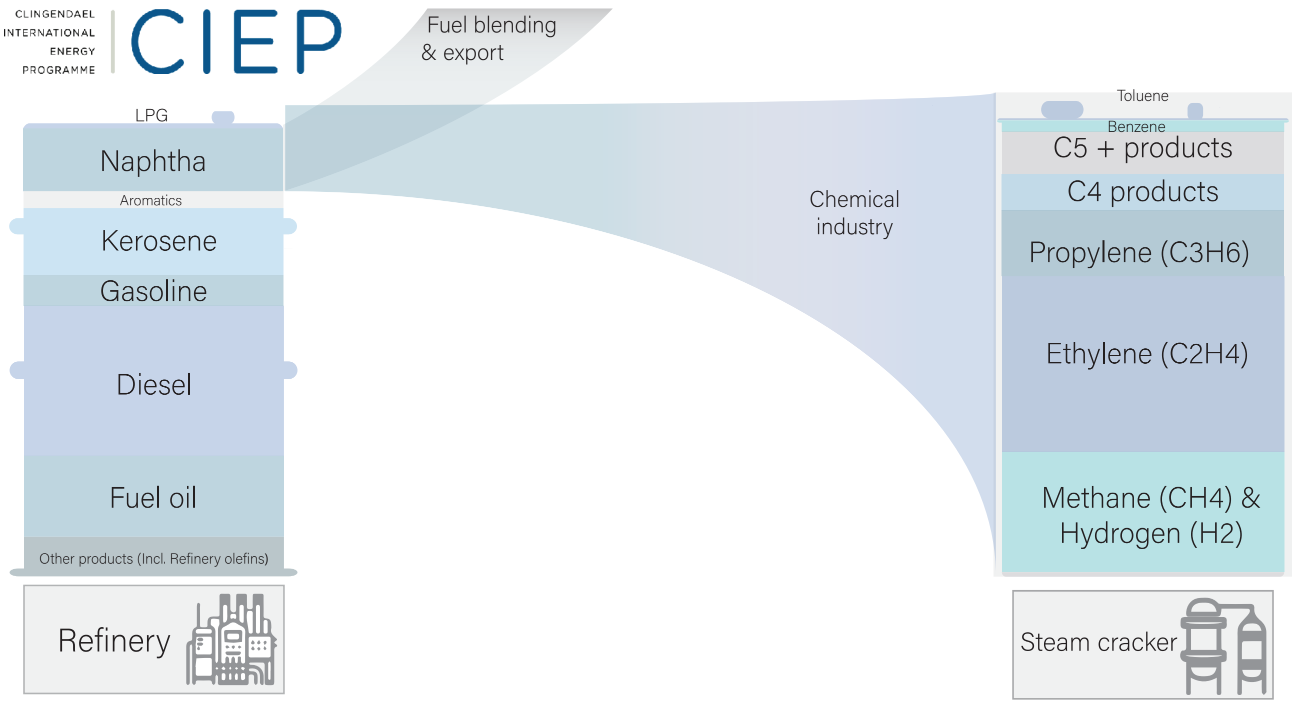


FIGURE 4 – ILLUSTRATING REFINERY AND STEAM CRACKER PRODUCT SLATES, BASED ON THE DUTCH BARREL.

CIEP-ANALYSIS BASED ON VARIOUS SOURCES INCLUDING CENTRAAL BUREAU VOOR DE STATISTIEK, 'AARDOLIEPRODUCTENBALANS 2015 – 2019'.

71 One of these refineries is currently studying the option of mothballing the site.

72 In this study, refineries have been classified as crude processing facilities that operate a distillation column exceeding 20kb/d of nameplate capacity and produce a 'wider' range of products (i.e., excluding specialty refineries).

STEAM CRACKING AND BASE CHEMICALS PRODUCTION

Steam crackers convert ('crack') hydrocarbons (both straight-chained and cyclical, often saturated) – such as those found in naphtha, NGLs and other steam crackers feedstocks – into shorter (often unsaturated) hydrocarbons such as ethylene and propylene, which can be used as building blocks for plastic production and, hence, are referred to as base chemicals. Varying depending upon the consumed feedstock, the long hydrocarbons are cracked into a specific product slate of olefins[73] and aromatics.[74] Using naphtha results in a balanced output of products, while the output produced by cracking ethane is limited primarily to ethylene.[75] In addition to being produced by steam crackers, refinery product slates also include olefins and aromatics, with the product shares depending on their configuration and grade of crude oil intake. For propylene, refineries are responsible for a significant share of the total production. Additionally, the aromatics plant integrated in the Botlek refinery in the port of Rotterdam produces large volumes of pure aromatics.

In the ARRRA cluster, there are currently 16 steam crackers in operation and one under construction, with a total production capacity of about 10 million tonnes of ethylene per year (MT/yr).[76] Steam crackers upgraded to take in higher shares of NGLs are located near the coast, as NGLs are imported by ship. In the coastal subcluster of Antwerp, one of the crackers has been reconfigured to allow it to run on ethane, butane or naphtha.[77] Here, advantaged feedstocks may account for over 50% of total supply. Included in the new cracker project in Antwerp is the construction of a propane dehydrogenation (PDH) unit to compensate for the lower yield of propylene by the ethane cracker, compared to a naphtha-fed cracker. The steam crackers in Zeeland are capable of using NGLs for the vast majority of their feedstock intake. Though not directly located at the coast, the steam crackers in Geleen also have the ability to import NGLs through their pipeline connections to the Belgian coast. Steam crackers deeply integrated in a complex refinery yield the benefit of optimizing site performance by exchanging hydrocarbon streams. This, however, may also partly hamper their ability to take in cost-advantaged feedstocks. Decades of developments and optimisation have also led to a deep integration of

73 Defined as 'acyclic and cyclic hydrocarbons having one or more carbon–carbon double bonds, apart from the formal ones in aromatic compounds' (IUPAC). The olefins group notably includes ethylene, propylene, butadiene and (iso)butylene, which consist of 2, 3, 4 and 4 carbon molecules, respectively.

74 Aromatics are cyclical hydrocarbons with double bonds, often typified by benzene (IUPAC). The group notably includes benzene, toluene and xylene, often referred to together as the 'BTX' group.

75 For an overview of typical yields per feedstock, refer to IEA (2018) 'The future of petrochemicals,' Figure 2.5.

76 Data: Petrochemicals Europe.

77 One of Total's two steam crackers in Antwerp has the ability to annually accommodate 200,000 tons of ethane imported from Norway.

steam crackers with their clients, a pattern also observed at refineries with aromatics units.

CHEMICAL CONVERSION AND PLASTIC PRODUCTION

Base chemicals form the building blocks of a great variety of plastics (Figure 5), including polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET) and a number of styrene polymers (PS, EPS, ABS & SAN). Collectively, these types of plastics comprise 41 million tonnes (MT), or 84% of annual European plastic demand.[78] While the number of (co)product options increases with the number of intermediates and processing steps as we go down the value chain, the majority of organic chemical products can be traced back to one of the olefins and aromatics.

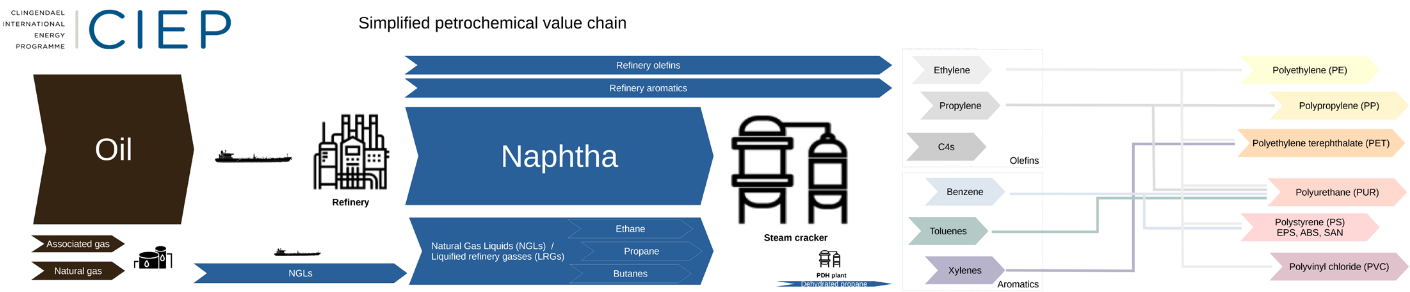


FIGURE 5 – SIMPLIFIED VALUE CHAIN FOR OLEFINS, AROMATICS, AND PLASTICS.

FROM CRUDE OIL, ASSOCIATED AND NATURAL GAS (IN BLACK, IMPORTED), TO SELECTED REFINERY PRODUCTS & STEAM CRACKER FEEDSTOCK (IN BLUE), TO OLEFINS & AROMATICS (IN SHADES OF GREY) TO THE SIX PLASTIC GROUPS THAT REPRESENT 84% OF EUROPEAN PLASTIC CONSUMPTION. (COLOURED).

The complexity and interdependencies of the industry can be illustrated by taking the six plastic types that we discuss here as examples. The polyolefins PE and PP are produced by polymerisation of ethylene and propylene, respectively. PE comes in a number of different grades, the main ones being high-density polyethylene (HDPE), low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE). As is the case for other plastic production plants, PE plants are integrated with steam crackers and other downstream units. Besides PE, ethylene can also be transformed into mono ethylene glycol (MEG), which produces PET when allowed to react with purified terephthalic acid (PTA), a xylene derivative. Additionally, ethylene can be

78 Based on 2019 data by Plastics Europe.

used to produce PVC via a route that uses chloride[79] and has vinyl chloride monomer (VCM) as an intermediate. Ethylene can, furthermore, be reacted with benzene to get ethylbenzene. In a propylene oxide styrene monomer (POSM) plant, ethylbenzene and propylene are converted into styrene and propylene oxide. Styrene acts an important monomer that can be converted in polystyrene (PS) and expanded polystyrene (EPS) through polymerisation. ABS and SAN are examples of co-polymers of styrene. These polymers are obtained by copolymerisation of styrene and another polymer.[80] The propylene oxide stream coming from the POSM plant can be used to produce polyols. In turn, polyols can be converted into PUR by letting the polyols react with methylene diphenylmethane diisocyanate (MDI), a benzene, or toluene diisocyanate (TDI), a toluene derivative.

Figure 3 shows the number of PE, PP, PET, PVC, polyols and MDI, and styrene production sites per subcluster. The spatial distribution of production capacity for various products also reveals the interconnectedness of the cluster, as it implies that product deficits and surpluses are compensated by transport. For example, all subclusters, except for Rotterdam-Moerdijk, have substantial PE production capacity. While Rotterdam has no PE capacity, it consumes more ethylene than the Moerdijk cracker can produce. This ethylene, imported via the Aethylen-Rohrleitungsgesellschaft (ARG) and Rotterdam C2 (RC2) pipelines, is used for PVC and styrene production, a sector in which the Rotterdam-Moerdijk cluster is sizable in relation to other subclusters.[81] Propylene pipelines in the western part of the ARRRA are also connected to the Feluy industrial area. Feluy houses the cluster's largest polypropylene plant but has no other plastic production on site, and, hence, could be considered a satellite site to the ARRRA cluster. This also applies to the PVC plant in Jemeppe.

In addition to the chemical plants included in Figure 3, North-West Europe is home to a number of 'biobased clusters.' These initiatives include Flanders biobased valley, Flanders.bio, Biobased delta, Northern Netherlands, CEF.NRW and BioNRW and complement the initiatives undertaken in the ARRRA subclusters. The local biobased clusters are united in a cross-border initiative named Bio Innovation Growth mega-Cluster or BIG-C. While biobased production capacity on a scale comparable to naphtha or NGLs-based production is a long way off, and despite the fact that these initiatives do not have pipeline access to the ARRRA, their institutions are certainly growing in the ARRRA cluster.

79 Chlorine is produced by electrolysis of brine in the ARRRA, predominantly using membrane electrolysis. EuroChlor (2020) 'Chlor-alkali industry review 2019-2020.'

80 Acrylonitrile in the presence of polybutadiene in the case of ABS, and acrylonitrile monomers in the case of SAN.

81 Note that these observations are made based on nameplate capacities. Annual production volumes of individual companies or sites are generally not publicized.

THE ARRRA CLUSTER: BEGGAR-THY-NEIGHBOUR OR BETTER TOGETHER?

From discussing the spatial distribution of refineries, base chemical production sites and chemical conversion plants, it becomes clear that, for activities performed throughout the ARRRA cluster, chemical sites are dependent on the activities performed by their industry peers up and down the value chain. Furthermore, while subclusters have their own characteristics and specific configurations, the types of plants and processes used are not entirely unique. Multiple subclusters have similar production capabilities. This overlap makes production in the ARRRA robust to, for example, maintenance or transportation issues such as periods of low river water. It also means, however, that, to a certain extent, production locations can be moved. If conditions are unfavourable for production in one subcluster, production can shift to another subcluster, especially due to the layout of the ARRRA's waterways and pipeline infrastructure and its exposure to international markets.

CONNECTED THROUGH INFRASTRUCTURE

Within the ARRRA, the terminals in the Port of Rotterdam fulfil a central role in importing crude oil, as the harbour can handle the largest crude tankers and has extensive crude storage and transport facilities. From Rotterdam, crude oil is transported to, amongst others, the Port of Antwerp via the Rotterdam-Antwerp Pipeline (RAPL).[82] This and other infrastructural connections between the subclusters are shown in Figure 6. Both ports house over 1000 kilometres of intra-port pipelines. The collective length of the pipelines that connect the ARRRA's Ports of Antwerp, Rotterdam-Moerdijk and Zeeland with the more-inland subclusters in Geleen, Cologne, Gelsenkirchen and Ludwigshafen are even longer. Generally, these pipelines transport hydrocarbons from the coast, inland (west to east). The Rotterdam Rhine Pipeline (RRP), which is an oil pipeline, brings crude to the clusters in Gelsenkirchen and Cologne. Additionally, the refineries in North Rhine-Westphalia source oil via the Nord-West Oelleitung (NWO).[83]

The Rhein Main Rohrleitung (RMR) system transports naphtha and other refinery products to and between refineries and steam crackers.[84] The Chemelot industrial

82 Rotterdam Antwerpen Pijpleiding N.V, RAPL.

83 Due to their long lifetimes, today's industry is still using and benefitting from some pipelines systems that had their foundations laid as early as the mid-20th century. Constructed originally by NATO for strategic purposes during the Cold War and later opened for commercial parties during peacetime, the Central European Pipeline System (CEPS) transports kerosine, gasoline and diesel. While technically capable of carrying naphtha, CEPS is not used for the transportation of cracker feedstock within the ARRRA.

84 The RMR can transport multiple petroleum products. Kerosene, gasoline and naphtha streams are transported in batches separated by rubber balls.

area in Geleen is connected to the Port of Rotterdam by the Pijpleiding Rotterdam – Beek (PRB). In addition, the Pijpleiding Antwerp – Limburg – Luik (PALL) is important to Chemelot, as it connects the site with the Port of Antwerp. Via this pipeline system, Geleen can source cost-advantaged NGLs. In contrast to their Belgium and Dutch counterparts, German steam crackers have pipeline access only to naphtha feedstock, not to NGLs.

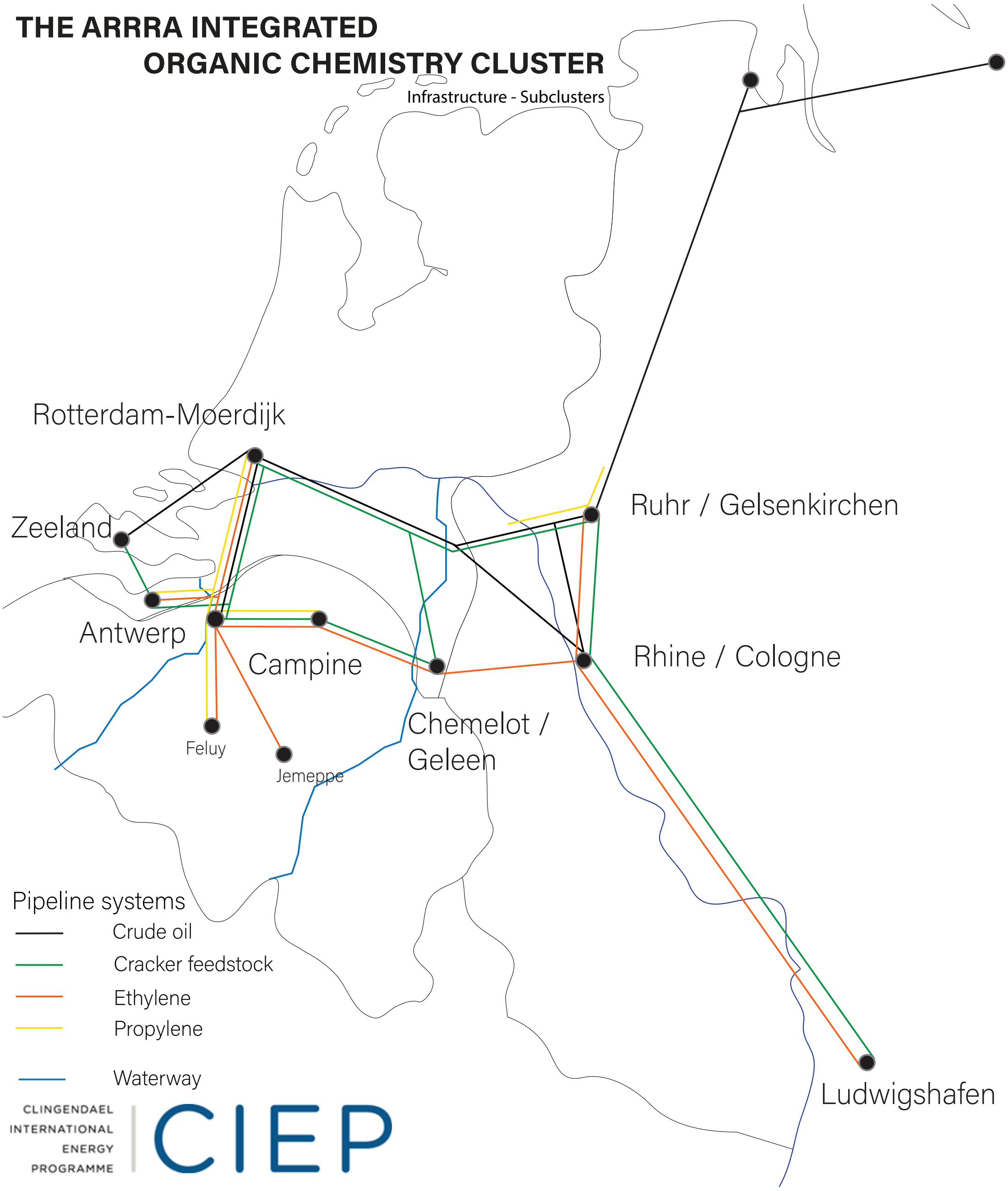


FIGURE 6 – THE ARRRA'S INFRASTRUCTURAL CONNECTIONS.

FOR THE TRANSPORTATION OF CRUDE OIL, STEAM CRACKER FEEDSTOCK AND STEAM CRACKER PRODUCTS BETWEEN SUBCLUSTERS.

All of the ARRRA's steam crackers are connected to the ARG pipeline, either directly or indirectly. [85] The cluster's ethylene backbone connects Antwerp directly with Geleen, Cologne and Gelsenkirchen, amongst others. Other subclusters and consumers are connected through (partly) private pipeline connections. These connections include the common carrier RC2 pipeline between Rotterdam and Antwerp and the BASF pipeline between the subclusters in Cologne and Ludwigshafen.[86]

Propylene is also transported via pipelines in both the eastern and western parts of the ARRRA, though there is a pipeline gap since these systems are not connected. In the western part of the ARRRA, propylene pipelines connect the Dutch subclusters of Rotterdam-Moerdijk and Zeeland with the subclusters in Antwerp and Campine and the site in Feluy. In the eastern part, a common carrier propylene pipeline system connects Moers, Duisburg, Gelsenkirchen and Marl. Chemicals are not only transported by pipeline systems. The other methods are waterways, railways and roads. Waterways, especially the Scheldt, the Meuse and the Rhine river, act as lifelines for industry in North-West Europe and, for example, allow for transportation of propylene to German sites.[87]

Since they provide a safe and reliable method to transport hydrocarbons, discussions of possible pipeline extensions take place on a regular basis.[88] In recent discussions, options were explored for the realisation of new propylene and LPG pipeline systems, as well as for new hydrogen and CO_2 networks.[89] In these discussions, it is worth keeping in mind that pipelines can transport feedstocks or products from both fossil and alternative sources. Molecules are colour-blind, so pipelines can transport biobased naphtha or propylene from recycled polymers similarly to how fossil feedstocks and products are transported today. This is illustrated by a first delivery of pyrolysis oil that was produced from used plastic to a terminal in Rotterdam.[90] This alternative cracker feedstock arrived from Spain by truck and was later transported to a steam cracker in Geleen.

85 ARG mbH & Co. KG.
86 Common carrier pipeline systems offer transportation services to any third party under a standard set of terms. This is in contrast to private pipelines that are not open to other parties on a non-discriminatory basis.
87 Chemical Parks in Europe, ECSPP.
88 E.g., a feasibility study into a propylene network to bridge the pipeline gap and connect sites in Belgium, The Netherlands and Germany was conducted in 1999. In 2007, the European Pipeline Development Company announced that it had decided to shelve the project due to the high cost involved.
89 Trilateral chemical region, Working Group Infrastructure.
90 Tank News International.

EMBEDDED IN A WEB OF INTERNATIONAL MARKETS

For the development of new infrastructure projects, as well as for general strategic planning, chemical companies and subcluster authorities seek guidance in the exploration of future demand profiles for chemical products. Economic and population growth and rising standards of living generally drive (future scenarios of) plastic consumption. Upstream, midstream and downstream chemical players generally formalise chemical trade in long-term contracts. Spot contracts for transportation through pipelines are priced significantly higher than their long-term counterparts.

With increased attention on plastic pollution and recycling targets, it seems that the societal appetite for plastic is changing. This is certainly the case for certain demand types, such as for single-use plastics in Europe. However, there are also growth markets for plastics, such as PVC and PUR, due to their use in construction and insulation. Moreover, it is worth considering that there is no single market for chemical products. Just as there are different international and regional markets for crude oil, natural gas, naphtha, NGLs, base chemicals and intermediates,[91] there is also a plethora of markets for plastics of various compositions (e.g., PP, PVC), qualities (e.g., food grade), shapes (e.g., flakes or fibres) and origins (e.g., virgin, recycled or biobased). These markets are highly interconnected through imports, exports, substitution options and links in production chains.

Drawing conclusions about the prospects of plastic demand is beyond the scope of this paper. An assessment that does justice to the complexity of market dynamics would require a comprehensive elaboration of, amongst others, the effect of shrinking liquid fuel markets on the availability of cracker feedstock, the effects of plastic substitution used to lower life-cycle emissions, as well as potential changes in policies and consumer behaviour. Additionally, such an assessment requires more insights in the prospects of alternative plastics (e.g., PLA, PBAT and PEF) and alternative feedstocks for plastic production (e.g., biomass, plastic waste or synthetic feedstocks).

GOVERNED BY MUTUAL INTEREST?

The preceding paragraphs have demonstrated that refineries, steam crackers and plastic production plants in the ARRRA cluster are highly interconnected through their infrastructural and value chain connections. The plastic value chains we analysed here are only a subset of a chemical industry that shows an even higher

91 Import of bio-MEG from the UK for PET production in Rotterdam-Moerdijk is an example of how (biobased) intermediates are traded internationally.

level of interdependence. In addition to private parties, there are numerous non-corporate stakeholders interested in changing the course of the chemical industry. As a result, developing policies for the industry in the ARRRA is complex. In this pluriform and dynamic setting, decisions are not easily imposed from the top down. Instead, governance in the cluster takes place in networks. These networks are active at multiple governance levels, are defined according to different criteria and collectively make up the ARRRA's governance. Taking this into account, a single actor in the ARRRA could wonder whether the environment in which the actor operates – the ARRRA chemical ecosystem – can actually be governed effectively.

Coming to decisions in pluriform networks of interdependent stakeholders is difficult. Nevertheless, the public policy literature provides us with various approaches to managing and – as we will do here – analysing decision making in networks.[92] One approach is that of instrumental governance.

Conceptually, instrumental governance involves the government bringing a policy instrument into play. This could include mandates, (environmental) taxes, subsidies, and quota obligations such as an emission trading scheme. However, in view of the earlier described characteristics of an ecosystem and the integrated nature of the ARRRA chemical cluster in particular, the consequences of such an approach would be difficult to predict, and the effectiveness and efficiency of instrumental governance are debatable. For example, a tax might lead to additional production in a subcluster at the other side of the border, while a mandate inhibiting the production of a specific chemical might lead to imports of chemicals with similar characteristics.

Two other approaches can be used to create a favourable climate for instrumental governance. The first is the network management approach, which involves governments altering the relations among actors. An example of this approach is the initiative in North Rhine-Westphalia, Flanders and the Netherlands to establish a 'trilateral strategy for the chemical industry.'[93] With this initiative, governments created a forum to discuss problems encountered in the different regions. While this network management approach could be effective in certain areas – for example, in

92 De Bruijn, J. A., and Ten Heuvelhof, E.F. (1995) 'Policy Networks and Governance' In: Institutional Design. Recent Economic Thought Series, Springer.

93 The Trilateral strategy for the chemical industry is an initiative of the Trilateral Chemical Region. On a strategic level, the region is represented by the Dutch Ministry of Economic Affairs and Climate Policy, the Flanders Department of Economy, Science & Innovation, the North Rhine-Westphalia Ministry of Economic Affairs, Innovation, Digitalization and Energy, and the industry organisations VNCI, VCI NRW and Essencia.

discussing problems related to scaling up electric cracker projects – it has so far proven to have a limited ability to align policy instruments.

It is likely that the initiative's inability to align policy instruments is rooted in its institutional design.[94] The region's main institutional framework – the trilateral strategy – does not match with the composition of the ARRRA cluster described in this chapter for several reasons.

First, not all the subclusters are included in the trilateral strategy through a governmental representative. While connected to the ethylene backbone, Feluy, Jemeppe and Ludwigshafen are not represented and, thus, cannot voice their input on how policy instruments could be used effectively. Second, ministerial representation is not aligned. While this might be understandable due to the geographic size of the regions and differences in institutional frameworks used in the different countries, the fact that Flanders, a region in Belgium, tries to find common ground with North Rhine-Westphalia, a state in Germany, as well as with the country of The Netherlands is inherently problematic. As the partners do not have access to and ownership of the same type of policy instruments, the chance that these will be aligned or even brought to the table is slim. Third, the current trilateral strategy makes it unclear what lines of communication are available for levels that are not formally involved. It is unclear for provinces in The Netherlands and Belgium which body to approach if they want to discuss issues with their counterparts in Germany. Hence, regional co-operation might be less likely, and the outcome could be the opposite of what was intended.

For these reasons, a second approach, the network restructuring approach, might be more appropriate for creating a forum in which policy instruments can be aligned. This approach seeks to alter 'the play's cast of actors,' as it involves changing the set of players that is active in a network. To achieve this change, considering a multi-level institutional design in which policy makers can discuss problems with colleagues who have access to the same policy instruments is recommended. The trilateral region could be redesigned in such a way that state- or province-level policymakers share the table with their foreign counterparts. Subsequently, issues could be discussed through existing frameworks within the three countries, followed by higher-level meetings such as those between national ministries. While this approach will not solve all forms of disagreement, it can make cooperation more effective, as

94 For background on institutional design theory see Goodin (1996) The Theory of Institutional Design, Cambridge University Press.

it creates an environment for negotiation and collaborative learning among more stakeholders.

BOX 4 – WHICH POLICY INSTRUMENTS CAN BE ALIGNED?

No matter which path is chosen, and independent of whether the institutional design of the trilateral strategy is reconsidered, aligning the various policy instruments between different countries, states, provinces, municipalities, and other governed entities is an inherently complex task. A plethora of policy instruments could be used to steer the chemical industry. Deciding which combination to use (at which level) requires additional research. In further research, at least three points should be considered.

First, as argued, using national policy instruments within the ARRRA cluster can be problematic, as they have the potential pitfall of displacing production from one country's subcluster to a subcluster located perhaps only a hundred kilometres down the pipeline. While country-specific measures, such as a national levy on 'avoidable emissions,' represent only one factor in a wider set of country-specific conditions, incentives and exemption, they do bear the risk of replacing production without reducing emissions. And this risk is linked to the additional burden that such instruments impose on producers. Providing a more level playing field by aligning policy instruments with those of neighbouring countries mitigates this risk.

Second, demand-side policy instruments, if consistently designed, provide a set of more effective mechanisms, as they may also limit end-of-life emissions. Such instruments can include targets and financial incentives affecting the share of biobased and recycled chemical products. These have to be well embedded in EU regulation on the single market and should be accompanied by an adequate formulation of targets, indicators and corresponding monitoring and evolution programs.

Third, strengthening the chemical industry's ability to decrease the potential GHG emissions embedded in the products they make requires financial support for research and development and pilot programs, in addition to subsidy schemes for early-phase exploitation. This should enable a scale-up of alternative feedstock initiatives, of which every subcluster has many.[95] A related intervention that could

95 See, e.g., IN4climate.NRW (2020) Chemical Plastics Recycling – Potentials and Development Perspectives or EN Zuid (2020) Groene chemie, nieuwe economie.

be considered by the three countries that house the ARRRA cluster could spur the scale-up of innovative projects by decreasing the relative costs of alternative feedstocks. Under article 24 of the ETS Directive, Member States may choose to opt in emissions from additional activities not covered by the EU ETS.[96] As emissions from incineration of municipal waste are currently not included in the ETS, including it would put a price on emissions caused by incinerated waste, and, as such, would level the playing field for alternative feedstock projects. As a prerequisite for this instrument, extensive 'leakage' of waste streams to outside of the cluster should be prevented.

All instruments require a governance framework that is suitable to the complexity of the ARRRA cluster.

PATTERNS IN A CHEMICAL ECOSYSTEM OF OBLIGED INDUSTRIAL SYMBIOSES

As hydrocarbons are transformed from feedstock into plastic and travel from terminal to chemical plant, they undergo an incredible number of transformations while flowing through pipelines and installations owned by many companies. While connections are plentiful, three key observations can be made based on the ecosystem description put forward in this chapter.

First, the analysis showed that refineries, base chemical production sites and chemical conversion plants depend highly on the activities performed by partners in the value chain. While subclusters have their own characteristics and specific configurations, the plants and processes used are not unique. This overlap in product portfolios contributes to the ARRRA's competitiveness and guarantees production during maintenance or external events. However, it also means that, to a certain extent, production can be relocated between subclusters. Since the ARRRA is so especially well-connected and embedded in international makers, unilateral use of national policy instruments may cause shifts in production activities.

Second, the analysis of the current ARRRA governance framework, from the perspective of network theory, revealed that while the establishment of the 'Trilateral Chemical Region' provides a forum to discuss problems encountered in different regions, the initiative's ability to align policy is limited since its institutional design

96 Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

does not match the composition of the cluster. In the current design, not all subclusters are formally represented in the initiative; the ministerial representation is not aligned; and formal communication lines linking the different levels of government are unclear. It would be good to consider an alternative, multi-level institutional design in which policy makers discuss problems with colleagues who have control over the same policy instruments.

Third and, perhaps, most fundamental, is the discussion of the ARRRA's chemical ecosystem from the perspective of complex systems theory,[97] which, as presented here, revealed its emergent properties.[98] The ARRRA is a cluster of subclusters that are collections of chemical productions sites, which, in turn, are a collection of chemical processes. These levels are interconnected through a network of pipelines and institutions. The state of the cluster, on a macro level, depends on the rules by which all the individual parts operate and on the ways in which the subclusters, sites and processes are connected. No single subcluster is competitive in a global sense: its competitiveness vis-à-vis clusters in the US, China or the Middle East arises or 'emerges' from the connections and relations between subclusters and the rules by which they are governed. In a similar way, the ARRRA's ability to evolve further into a cluster that produces chemicals with a substantially lower carbon footprint and its ability to provide well-paying jobs to the regions depends on the rationales behind lower-level choices (e.g., the criteria that producers use to select the chemical conversions to be performed) and connections between subclusters (e.g., by pipeline). In this regard, it is fundamental to consider that – similar to natural ecosystems of obliged symbioses[99] – the ARRRA's survival depends on the survival of its parts. While its various parts might conflict, certain collections of the ARRRA's parts should be sustained, as the destabilisation of the ecosystem might lead to its uncoordinated collapse.

97 Complex system theory is an approach to science that studies how relationships between parts give rise to the collective behaviors of a system and how the system interacts and forms relationships with its environment. For a more detailed description, see, e.g., Bar-Yam, Y. (2004) Making things work: solving complex problems in a complex world NECSI Knowledge Press.

98 In complex systems theory, emergent properties are properties of a system that are not apparent from its components in isolation but that result from the dependencies, interactions or relationships they form when placed together in a system. They are traits that a collection of parts or a complex system has, but that the individual members do not have.

99 In obliged symbioses, one or both of the members of the interaction depend entirely on each other for survival.

CONCLUSION

The organic chemical industry finds itself stranded between increasingly stringent targets for the reduction of direct GHG emissions and the ambition to produce chemicals that enable the reduction of indirect emissions. Additionally, the global landscape is changing due to the revitalisation of the US chemical sector by the shale revolution, China's aims for decreased reliance on imports of base chemicals and intermediates, and the fact that governments in the Middle East and Russia view chemical production as an economic diversification opportunity. In Europe, the chemical sectors' centre of gravity lies in the Antwerp, Rotterdam, Rhine, Ruhr Area (ARRRA). With a heritage of hydrocarbon transformations that spans over a century, the continuing supply of desired and useful products throughout the 21st century requires the reimagination of value chains.

In itself, a feedstock shift would not be new to the chemical industry. While an historic perspective on these transitions does not dictate a line of action going forward, it does reveal the dynamics of change. The ARRRA cluster's roots are in the regional availability of coking by-products. Chemistry's toolbox provided opportunities to convert these by-products into desired products and, thus, to monetise previously undervalued steams. As oil rose to importance as an energy source, by the mid-twentieth century, carbochemistry was outcompeted by petroleum-based chemistry, which used undervalued refinery fractions. More recently, the abundance of natural gas liquids produced as by-product in the (shale) oil and gas sector has driven a partial second feedstock shift. For each of these feedstocks, the chemical industry did not create the value chains that produced them. Instead, changes outside the chemical sector yielded these feedstocks as cost-effective by-products. The chemical industry seized the opportunities presented by the residual streams.

In the face of these feedstock changes, the ARRRA as a cluster showed resilience. This resilience can be explained from a purely technical perspective, as well as from a wider, more institutional perspective. Technically, chemical plants operate most efficiently when clustered, as that enables the exchange of the plethora of feedstocks and products, the optimization of heating and cooling, and shared utility, maintenance and processing services. From a wider perspective, it follows that clusters encompass a broader set of institutions creating critical masses that flock –

and stick – together in one location. Following both lines of reasoning, the ARRRA's infrastructure, specifically its web of waterways and pipelines, has been vital to the competitiveness of the subclusters. Along with clustering and market forces, public involvement has been a constant and crucial factor for the chemical sector. Governmental action goes beyond simply providing infrastructure and 'the right conditions,' as it pushes corporate undertakings amongst others in the form of support for research and development and early-phase investments.

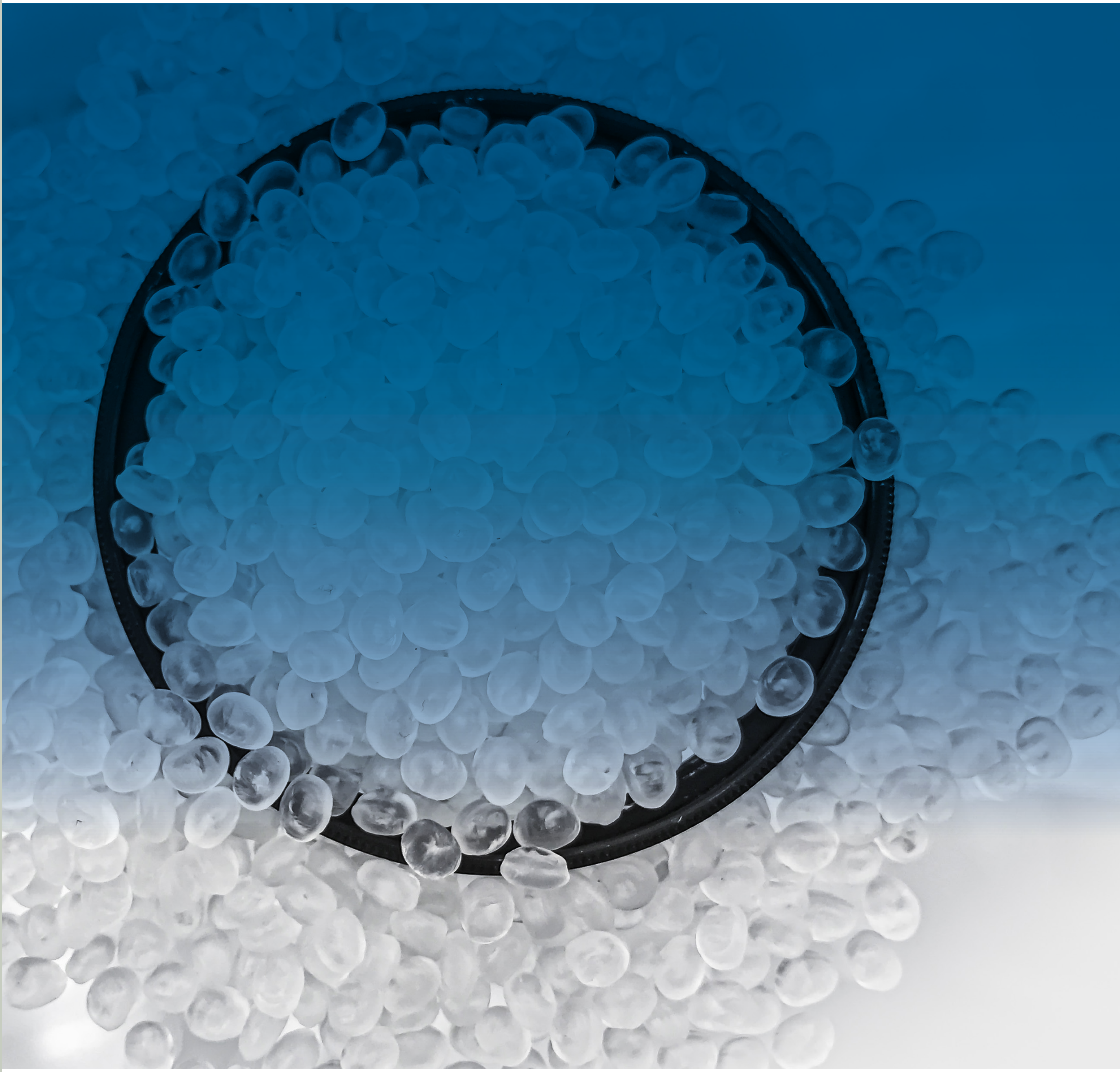
Tracking molecule flows from ports to products reveals that the ARRRA refineries, steam crackers and chemical conversion plants are all highly interdependent with their value chain partners. By examining the distribution of production sites, it becomes clear that, while subclusters have their specific features and compositions, the plants and processes used in each subcluster are, in themselves, not unique. Especially since the ARRRA is so well embedded in infrastructural networks and international markets, overlap in product portfolios enables production to shift, to a certain extent, from subcluster to subcluster during maintenance or external events. Due to this overlap, a shift in production may also be enacted by unilateral employment of national policy instruments, providing an argument for further alignment of national instruments. In this regard, the Trilateral Chemical Region initiative provides an excellent forum to discuss problems encountered in different regions. Its current institutional design, however, limits its ability to align policy instruments, as not all subclusters are formally represented; ministerial representation is not aligned; and formal communication lines linking governmental layers are unclear. It is recommended to consider an alternative, multi-level institutional design in which policy makers discuss problems with colleagues who have control over the same policy instruments.

By contrasting the patterns that emerged from our analysis of the ARRRA's chemical ecosystem with the discussions held in the contemporary energy policy discourse we can make three observations. First, the ARRRA chemical cluster developed out of local interactions and was not designed by a central authority. Nor will any future changes in the cluster be the result of a top-down techno-economic optimalisation. Policy makers and subcluster representatives who focus their attention primarily on the most favourable technologies in their marginal abatement cost curves would benefit from widening their perspective by including the dynamics and interactions described in this paper in their analysis. In this regard, we recommend considering system options that build value chains and create new markets, even if these options are not the most efficient solution from a short-term, techno-economic perspective.

Second, considering this more extensive set of options requires a more integral understanding of alternative feedstock pathways, including insights into how these pathways interact with the existing value chains. Moreover, it requires not only knowledge of their current value chain partners, but also of potential new value chain partners in adjacent industries, such as the electricity, steel, agriculture, and fertilizer sectors. While the ARRRA's chemical industry could overcome the historic hurdle of establishing a dedicated value chain for its feedstock, anticipating a scenario in which it again relies on adjacent industries would be wise.

Finally, the chemical sector's relationship with the oil and natural gas sector is complex and bi-directional. For the oil sector, chemicals have often been pinpointed as a key driver of future oil demand growth. However, limited domestic demand growth for plastics and global competition makes this unlikely to be the case in Europe. On the other hand, structural changes in other demand sectors, such as mobility and heating, could impact feedstock costs and availability for the chemical sector.

For Europe, the policy instruments that will be most effective in the midst of all these developments are those that serve the interests of the environment and simultaneously ensure the cluster's integration. As such, global competition in well-regulated European markets might prove to be the catalyst for the ARRRA's feedstock transition. It is up to the members of the ARRRA chemical ecosystem to provide the preconditions for effective collaboration and to anticipate linking chemical value chains with activities outside the classical sector borders.



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