HYDROGEN TO BE

GEOPOLITICAL AND SOCIAL IMPLICATIONS OF EMERGING LOW-CARBON HYDROGEN TRADE AND SUPPLY NETWORKS IN THE ARRRA SUPERCLUSTER

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1 CIEP, 2022. *Managing Future Security of Low Carbon Hydrogen Supply*. https://www.clingendaelenergy.com/publications/publication/managing-future-security-of-low-carbon-hydrogen-supply.

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SUMMARY

INTRODUCTION

The Russian invasion of Ukraine in February 2022 and the resulting Western sanctions against Russia have brought geopolitics and energy to the forefront of the public debate. The current global energy crisis has reiterated that geopolitical and societal dynamics have an immense influence on energy systems, and consequently, the energy transition. As is now evident, decades of European energy policy and, by implication, societal stability across Europe, was upended in a few months.

Thinking beyond current trends and near-term developments is more important than ever. This is particularly important in the energy sector, where high capital investments and long lead times necessitate robust long-term planning. Moving from the COVID-19 pandemic to the current energy crisis, the world is unevenly preparing for another crisis: a much slower unfolding, climate crisis. Transforming the energy system while minimising disruption to energy services is proving a difficult task. Hydrogen is already a part of this transformation, but its exact role in the future energy system remains unclear.

EXPLORING PATHWAYS THROUGH SCENARIOS

Formulating coherent scenarios about what future geopolitical and societal dynamics might look like, can help understand how hydrogen value chains and trade networks will emerge in uncertain and complex situations. This project therefore created scenarios **so companies, governments and business networks can develop strategies to robustly position themselves in the future low-carbon hydrogen value chains and markets**. This project addresses the implications for the Amsterdam-Rotterdam-Rhine-Ruhr-Antwerp (ARRRA) region, but derives strategic recommendations specifically for stakeholders active in the Rotterdam port-industrial cluster.

The research aims to answer the following question:

How will geopolitics shape the emergence of hydrogen trade and supply networks into the ARRRA supercluster and what effect will this have on key actors and on Dutch society in the period between 2025 and 2040?

The research used the 8-step scenario planning approach to help formulate answers to this question. It identified what is at stake, for whom, and in at what time horizon with respect to this research question. Using this analysis, it identified the most significant exogenous forces driving the development of low-carbon hydrogen supple and trade networks in the ARRRA region. This resulted in 20 key social, economic, environmental, political and technological forces (the SEEPT forces).

Social	Economic	Environmental	Political	Technological
S1: Social structure	**EC1**: CO_2 abatement policies	**ENV1**: Climate change-induced extreme weather events	**P1**: Leadership in hydrogen and hydrogen technology development	**T1**: Learning curve for non-H_2 electricity storage
S2: Public acceptance of the energy transition	**EC2**: Stability of global financial markets	**ENV2**: Scarcity of raw materials	**P2**: Degree of global cohesion	**T2**: Access to key hydrogen technologies
S3: Energy (distribution) justice	**EC3**: Extent of globalisation	**ENV3**: Land and water availability	**P3**: Rules setters in global markets	**T3**: Emergence of intercontinental energy supergrids
S4: Availability of human capital	**EC4**: Industry relocation	**ENV4**: Sustainability pathways	**P4**: Energy security in north-west Europe	**T4**: Emergence of high-energy digital appliances

OVERVIEW OF THE SEEPT FORCES

THE FOUR SCENARIOS AND HYDROGEN MARKET DEVELOPMENTS

From the SEEPT forces, six (S1, ENV4, P1, P3, P4 & T2) were prioritised as critical uncertainties to underpin four distinct scenarios of how the world might look like around 2040, described by looking back at key developments. Each scenario is summarized below, followed by the expected hydrogen market developments per scenario and their implications for low-carbon hydrogen trade and supply network development.

The **Revival of the Rhineland Model** describes a scenario in which a post-World War II and a pre-Washington Consensus market system flourished and in which the Rhineland social market economic model prevailed in north-west Europe. This economic transition, enabled by continuing US dominance, but where the US was no longer actively lobbying to maintain open global markets. Nevertheless, the EU aligned with the US. Environmental concerns became secondary to energy security and affordability, and economic recovery from the 2020 pandemic and the energy crisis that began in 2022. European political rhetoric centred on funding wages, redistributing wealth, and social welfare which was achieved through higher corporate taxes. Energy security was strengthened at high government expense.

Low-carbon hydrogen market development was driven by pursuing pragmatic sustainability and affordability. The energy transition took many years to get going, but gradually accelerated from 2030 onwards. Industry set the pace of hydrogen adoption. Hydrogen was reserved for energy-intensive industries. Demand was mainly met from large-volume imports procured from the global market, and supplemented by low-volume regional production. There was little variety in the value chain, based mainly on a few key technology advancements for low-carbon hydrogen. This split focus achieved moderate energy security, but with continued dependence on imports, moderate affordability, and low sustainability. Climate neutrality was only reached between 2060 and 2070.

In **The Right of Sun Tzu** scenario, the world moved into a China-led situation after a power struggle between the US and China. Changes in the geopolitical balance in the Middle East reinforced a period of global bipolarism between East and West, where China increasingly took the lead. The decline of the US hegemony became evident around 2040, where China began to set the tone in international affairs and global trade. EU members split on which bloc to align with: north-west Europe leant across the Atlantic, while south and south-east Europe leant towards China. Decarbonisation was not always a priority in the bipolar world, in which regional conflicts diverted attention and resources from climate change mitigation and adaptation. Nevertheless, under Chinese leadership, the world slowly moved towards carbon neutrality after 2040.

Market development was driven by energy security logic. Throughout the 2030s, ongoing concerns for energy security encouraged regional hydrogen markets to expand. Innovation and uptake of various low-carbon hydrogen technologies contributed to a forced and continued acceleration of the energy transition. Hydrogen served energy-intensive industries and the power sector, from high regional production and modest imports. North-west European imports came from the transatlantic market, with some value chain variety. This resulted in moderate energy security and sustainability, with climate neutrality reached between 2050 and 2060, but at the expense of low affordability.

In the **Europe's Eureka** scenario, a globally permissive trade environment emerged in which diplomatic breakthroughs drove countries behind the common, EU-led goal of addressing climate change. The EU successfully bet on the transition to ride out the impact of the 2022 energy crisis. European governments, elected by collectivist societies envisioning a green future, took a more prominent role in managing their economies in pursuit of idealistic sustainability goals. The access to key energy technologies and critical raw materials at low costs enabled Europe's energy transition but meant that development slowed in countries already lagging behind.

Market development was driven by a combination of energy security and idealistic sustainability values. The energy transition accelerated from incremental to exponential in the 2030s. Innovation-led cost reduction in hydrogen technologies resulted in uptake in energy-intensive steel and chemical industries, the power sector, transport and mobility, and in the built environment. This was serviced both by high regional production and large import volumes coming from a varied global market. Supply diversity led to high energy security, innovation-led cost reduction increased affordability substantially, and systemic change resulted in high sustainability with neutrality reached around 2050.

The **Broken Bridges** scenario sketches a shrinking and incohesive world, in which nations focused on domestic problems and national interests. Europe found itself on its own, which continued to fracture the EU after it was unable to overcome the energy crisis. The US presidency swung to the right once again, and the US became disinterested in climate change mitigation and in Europe. The EU reopened negotiations with Russia over its security demands. The 2030s were characterised by fragmentation and trade in distinct trade blocs. This deglobalisation process was interwoven with incoherent north-west European attempts to reduce emissions and become an international norm setter on decarbonisation. These efforts were set to fail, partly due to the surge of green colonialism sentiments in developing countries.

Market development was driven by idealistic sustainability values, with the market initially taking off quickly. However, it soon stagnated for a long period, picking up only after 2040. Hydrogen was only in demand by a downsized energy-intensive industry in the ARRRA region, and was serviced by modest regional production and low import volumes. The regional market demonstrated low value chain variety and innovation in key (green) hydrogen technologies was not sufficient. Pursuing sustainability at all-costs resulted in just that, high costs. Consequently, energy security and affordability remained low up to 2040, despite that carbon neutrality was reached around 2050, but largely due to the demise of European industry.

STRATEGIC OPTIONS FOR STRENGTHENING THE ROTTERDAM PORT-INDUSTRIAL CLUSTER

The four scenarios point to perceived certainties and uncertainties in hydrogen market development. In the light of these, five scenario-transcending strategies can be formulated to address concerns across all or most scenarios. These are the more robust no-brainers that the actors in the port-industrial cluster can execute in any case. There are also three scenario-specific strategies that work in only two of the four scenarios, and are therefore riskier. Implementing all these strategies will require active effort from different stakeholders. Coordination, if not collaboration, will be key for the cluster's sustained survival in an increasingly uncertain world.

SCENARIO-TRANSCENDING STRATEGIES

1. **Significantly expand regional production of renewable electricity and hydrogen**: all scenarios highlight that security of supply can no longer be taken for granted. This necessitates investment in electricity and hydrogen production, even despite limited space and the risk that hydrogen use does not materialise at scale. Vertical integration of hydrogen production, with long offtake agreements, can provide some risk mitigation.

2. **Diversify imports in terms of suppliers, energy sources and carriers**: with growing geopolitical and trade barriers, energy flows may be disrupted and assets abroad may be stranded. For future hydrogen users and importers, such as the chemical, steel, refining and transport sectors, supply diversification is critical. The scenarios highlight that from a security of supply perspective, investments in the transatlantic basin and southern Europe are most robust. The Middle East and northern Africa may be riskier. But if deglobalisation intensifies, this region may become an important export hub for Europe, and should therefore also be a focus of European energy and climate diplomacy.

3. **Invest in optionality and multi-functionality of terminals, conversion, storage, infrastructure and machinery**: in the energy transition, there is no silver bullet, and actors in the Rotterdam port-industrial cluster should not put 'all their eggs in one basket'. For users of hydrogen, this optionality means flexible offtake agreements, or offtakes with flexibility clauses. For grid operators, this means multi-functional and multi-directional infrastructure. This includes adapting gas pipelines, new or refurbished, for hydrogen and to service other mixtures, such as methane, hydrogen sulphide and ammonia. Existing fossil fuel infrastructure, such as LNG terminals, should be adapted to handle ammonia and other hydrogen derivatives, but without unnecessarily prolonging fossil fuel use.

4. **Invest in backup and redundant hydrogen production, conversion, storage and infrastructure capacity**: increased optionality should be complemented with building in redundancies, such as backup power generation, strategic energy reserves or pipelines not operating at full capacity. Redundancy is seen as costly, but costs are not the same as value. The value provided by redundancy should be built into investment decisions.

5. **Double down on circularity**: while already in progress, doubling down circularity can eliminate some external (energy) dependencies. This can be done by attracting new business and service providers, and co-investment in port infrastructure required for transporting materials, molecules and energy across the cluster. The Rotterdam Port Authority can support knowledge sharing, for example, on improving collecting, sorting and processing for sparce materials such as platinum, and scaling up innovations beyond pilot projects. However, circularity will also create new physical and relational interdependencies.

SCENARIO SPECIFIC STRATEGIES

6. **Replace current grey hydrogen use with low-carbon hydrogen and fully embrace the transition in other industrial segments**: replacing current grey hydrogen demand in the chemical industry is a low-regret strategy. It can serve as an important signal for low-carbon hydrogen adoption in other sectors. It also makes a meaningful statement to governments and society that the sector is embracing the energy transition as a proactive rather than compliant partner. This is important, as none of the scenarios guarantee a social and political licence to operate for large (chemical) industries in the ARRRA region.

7. **Increase investments in and control over strategic transition resources**: a successful hydrogen transition requires strategic transition materials, technologies and skilled labour to be available and affordable. Under the Right of Sun Tzu and Broken Bridges, north-west European governments need to increase diplomatic and trade efforts with critical raw material producing countries, and start monitoring the ARRRA region's material and technology needs as well as import dependencies. This includes playing to north-west Europe's strengths, by prioritising innovation policies and programmes around next generation materials and clean technologies. Protectionism rules, particularly to prevent (early) foreign take-over of strategic companies, may be needed. This includes prioritising security and stability in industrial policy, by maintaining, starting or reshoring critical processes. However, this strategy has its risks, and does not apply in all scenarios. Protectionism is expensive, especially when costs are socialised and returns privatised, moreover, the desirability of protecting inefficient industries is also questionable.

8. **Collaborate with other ports in the ARRRA region for import and trade of hydrogen and hydrogen derivatives**: the energy transition is a challenge too large to be tackled by a single port-industrial cluster alone. Under the Right of Sun Tzu and Europe's Eureka, and in the context of frequent global supply chain disruptions and changes, close collaboration can build resilience in the ARRRA region. This would involve data sharing and simultaneous adoption of new technology to improve coordination. It would also require some degree of intra-regional port specialisation, for example, with the Port of Rotterdam using its proximity to offshore underground storage for hydrogen or carbon capture and storage.

SAMENVATTING

INLEIDING

De Russische invasie van Oekraïne in februari 2022 en de daaropvolgende Westerse sancties op Rusland hebben geopolitiek en energie weer in de schijnwerpers gezet. De huidige wereldwijde energiecrisis brengt in herinnering dat geopolitiek en maatschappelijke dynamiek grote invloed hebben op energiesystemen, en daarmee op de energietransitie. In een aantal maanden tijd is het Europese energiebeleid van de afgelopen decennia en de stabiliteit van de Europese samenleving in een compleet ander licht komen te staan.

Zo lijkt het relevanter dan ooit om verder dan de huidige trends en korte-termijnontwikkelingen te kijken. Dit geldt zeker voor de kapitaalintensieve energiesector, waar enorme investeringen en lange doorlooptijden een robuuste lange-termijn visie noodzakelijk maken. Op weg van de COVID-19-pandemie naar de huidige energiecrisis, bereidt de wereld zich in verschillende mate voor op een nieuwe crisis: een zich veel langzamer ontvouwende klimaatcrisis. De huidige crisis maakt duidelijk dat het aanpassen van het energiesysteem en het tegelijkertijd betrouwbaar houden van de energievoorziening een lastige opgave is. Waterstof is al onderdeel van het veranderproces, maar de precieze rol van waterstof in het energiesysteem van de toekomst is nog niet geheel duidelijk.

PADEN VERKENNEN MET SCENARIO'S

Om te begrijpen hoe waterstofwaardeketens zich kunnen ontwikkelen in een onzekere toekomst helpt het om scenario's te formuleren daarvoor, tegen de achtergrond van verschillende denkbare geopolitieke en maatschappelijke contexten. Dit project schetst dergelijke scenario's om bedrijven, overheden, en bedrijfsnetwerken te ondersteunen in het ontwikkelen van strategieën om zich robuust te positioneren in de toekomstige koolstofarme waterstof waardeketens en markten. Het project verkent de gevolgen voor het hele Amsterdam-Rotterdam-Rijn-Roer-Antwerpen (ARRRA) gebied, en voorziet in specifieke aanbevelingen voor de partijen die actief zijn bij het Rotterdamse Haven-Industriële Cluster (HIC).

Het onderzoek beoogt de volgende vraag te beantwoorden:

Hoe zal geopolitiek de totstandkoming van waterstofhandels- en aanbod-netwerken naar het ARRRA-supercluster vormen en welke implicaties heeft dit op de belangrijkste partijen, en op de Nederlandse samenleving, in de periode van 2025 tot 2040?

Het onderzoeksteam gebruikte een methode voor scenario-ontwikkeling in acht stappen om deze vraag te beantwoorden. Deze aanpak maakte helder wat er op het spel staat, voor wie, en in welke tijdspanne. Hiervoor zijn de belangrijkste exogene krachten die inwerken op de totstandkoming van ketens voor de voorziening van koolstofarme waterstof naar het ARRRA-gebied in kaart gebracht. Dit bracht het onderzoeksteam tot een twintigtal sociale, economische, milieu, politieke en technologische (SEEPT) krachten.

Sociaal	Economisch	Milieu	Politiek	Technologisch
S1: Sociale structuur	**EC1**: CO_2-reductiebeleid	**ENV1**: Door de klimaatverandering veroorzaakte extreme weers-omstandigheden	**P1**: Leiderschap in ontwikkeling van waterstof en waterstof-technologie	**T1**: Leercurve voor (niet H_2) elektriciteits opslagtechnolo-gie
S2: Maatschappelijke acceptatie van de energietransitie	**EC2**: Stabiliteit van financiële markten in de wereld	**ENV2**: Schaarste aan grondstoffen	**P2**: Mate van globale samenwerking	**T2**: Toegang tot waterstof sleutel-technologieën
S3: Energie (verdelings)-rechtvaardigheid	**EC3**: Mate van globalisering	**ENV3**: Beschikbaarheid van land en water	**P3**: Bepalers van standaarden in wereldmarkten	**T3**: Ontwikkeling van intercontinentale supernetwerken voor elektriciteit
S4: Beschikbaarheid van menselijk kapitaal	**EC4**: Relocatie van industrie	**ENV4**: Duurzaamheids-paden	**P4**: Energiezekerheid in Noordwest-Europa	**T4**: Opkomst van energie-intensieve digita-le toepassingen

OVERZICHT VAN DE SEEPT-KRACHTEN

DE VIER SCENARIO'S EN WATERSTOFMARKTONTWIKKELPADEN

Zes van deze krachten (S1, ENV4, P1, P3, P4 & T2) zijn door het team beoordeeld als kritische onzekerheden en vormen daarmee het startpunt voor het construeren van de vier scenarios voor de wereld rond 2040. De scenario-narratieven zijn geschreven als een terugblik vanuit 2040 op ontwikkelingen in de voorgaand.

De **Wederopstanding van het Rijnlands Model** geeft een proces weer dat uitmondde in een economische ordening die overeenkomsten vertoont met de naoorlogse en pre-Washington-consensus periode. Het Rijnlandse sociaaleconomische marktmodel was prominent in Noordwest-Europa. Deze economische transitie werd mogelijk door de blijvende hegemonie van de Verenigde Staten, die zich echter niet in dezelfde mate als voorheen inzetten op volstrekt open wereldmarkten. De EU en de VS bleven ondertussen wel strategische partners. Zorgen over het milieu werden overschaduwd door zorgen over energiezekerheid en betaalbaarheid, en door het economisch herstel van de 2020 pandemie en de energiecrisis die in 2022 uitbrak. De Europese politieke retoriek richtte zich op inkomenszekerheid, herverdeling van welvaart, en maatschappelijk welzijn, door middel van hogere lasten voor het bedrijfsleven. Energiezekerheid verbeterde op kosten van de overheid.

Waterstofmarktontwikkeling werd gedreven door een pragmatische invulling van het streven naar duurzaamheid en betaalbaarheid. De energietransitie kwam langzaam op gang, maar versnelde vanaf 2030 gestaag. De industrie bepaalde het tempo van de adoptie van waterstof. Waterstof werd vrijwel uitsluitend benut in de industrie. In de vraag werd voornamelijk voorzien door grote volumes aan importen van de wereldmarkt, aangevuld met beperkte volumes die regionaal werden geproduceerd. De combinatie van importen en lokale productie voor industriële consumptie leidde tot aanvaardbare energiezekerheid, redelijke betaalbaarheid, en beperkte duurzaamheid. Een klimaatneutrale Europese samenleving komt pas in beeld tussen 2060 en 2070.

Het Gelijk van Sun Tzu voorziet een wereld die geleid wordt door China, na een machtsstrijd met de Verenigde Staten. Verschuivingen in de geopolitieke balans in het Midden-Oosten vergrootte de bipolaire verhoudingen tussen het Oosten en het Westen, waarbij China in toenemende mate de leiding nam. De afgenomen hegemonie van de Verenigde Staten werd echt duidelijk rond 2040, toen China de toon begon te zetten in het internationale verkeer en wereldhandel. De EU-lidstaten tonen zich verdeeld over de te volgen richting. Noordwest-Europa beweegt sterker richting de Atlantische wereld, terwijl Zuid- en Zuidoost-Europa zich meer tot China richten. Het streven naar lage CO_2-emissies heeft niet altijd de prioriteit in deze bipolaire wereld. Regionale conflicten eisen voortdurend aandacht en middelen op, ten koste van klimaatmitigatie en -adaptatie. Toch streeft de wereld na 2040 geleidelijk verder naar klimaatneutraliteit onder Chinese leiding.

De waterstofmarktontwikkeling volgde de logica van energiezekerheid. In de jaren 2030 versterkten voortdurende zorgen daarover de groei van regionale waterstof-markten. Innovatie en adoptie van diverse koolstofarme waterstoftechnologieën droegen bij aan een ingrijpende en steeds snellere energietransitie. Waterstof werd geconsumeerd in de energie-intensieve industrie en de elektriciteitssector, en kwam in hoge mate van regionale productie en in wat mindere mate van importen. De importen naar Noordwest-Europa kwamen uit de Atlantische markt, met enige verscheidenheid in de vorm van de waardeketens. Dit leidde tot redelijke energiezekerheid en duurzaamheid en het bereiken van klimaatneutraliteit van Europa tussen 2050 en 2060.

Europa's Eureka kreeg vorm in een gunstige context voor de wereldhandel. Doorbraken in diplomatie maakten het mogelijk dat uiteenlopende landen zich schaarden achter een gezamenlijk EU-geleide strategie voor het beperken van de klimaatverandering. De EU zette succesvol in op de transitie als antwoord op de energiecrisis van 2022. Europese regeringen, gekozen in een collectivistische tijdsgeest door burgers die een groene toekomst voor hun zagen, speelden een grote rol in het reilen en zeilen van de Europese economie, terwijl ze duurzaamheidsidealen gestalte gaven. De zeker gestelde toegang tot betaalbare sleuteltechnologieën in het energiedomein en kritische grondstoffen stelden Europa in staat om haar energietransitie te realiseren, hoewel dit de beweging in andere landen die al achterliepen verder vertraagde.

Waterstofmarktontwikkeling werd gedreven door een combinatie van energiezekerheid en ideële duurzaamheidswaarden. De energietransitie versnelde exponentieel in de 2030s. Innovatie-gedreven kostenreducties in waterstoftechnologieën mondden uit in een brede waterstofadoptie in de energie-intensieve staalindustrie, in de chemie, in de elektriciteitssector, voor transport en mobiliteit, en in de gebouwde omgeving. In de vraag van deze gebruikers werd voorzien door zowel ruime regionale productie als door grote importvolumes van een breed scala aan aanbieders in de wereldmarkt. Diversificatie van aanvoer leidde tot grote energiezekerheid. Innovatie-gedreven kostenreducties leidden tot een wezenlijk verbeterde betaalbaarheid, en de systemische verandering van economie en samenleving resulteerde in uitstekende duurzaamheid. Klimaatneutraliteit werd in Europa bereikt rond 2050

Verwoeste Bruggen waren het recept voor een steeds kleiner wordende en onsamenhangende wereld, waarin veel landen zich in de eerste plaats richtten op hun binnenlandse problemen en het nationaal belang. Europa kwam alleen te staan nadat de unie niet goed kon herstellen van de energiecrisis, wat keer op keer tot meningsverschillen tussen de EU-lidstaten leidde. Het nieuwe presidentschap in de VS nam een afslag naar rechts en het land raakte minder geïnteresseerd in het beperken van klimaatverandering en de relaties met Europa. De EU heropende de gesprekken met Rusland over veiligheidsgaranties. De jaren '30 werden gekenmerkt door fragmentatie, zodat handel in toenemende mate binnen de blokken in de wereld plaatsvond. Dit proces van de-globalisering kwam samen met incoherente pogingen van Noordwest-Europa om haar emissies te reduceren en om de internationaal de standaarden te bepalen in dat kader. Deze inspanningen waren echter tevergeefs, ook door de snelle opkomst van sentimenten rond groen kolonialisme in ontwikkelingslanden.

Waterstofmarktontwikkeling werd gedreven door ideële duurzaamheidswaarden, die initieel succesvol waren. Er brak echter snel een periode van stagnatie aan, die pas werd doorbroken door een nieuwe groeispurt na 2040. Het gebruik van waterstof vond alleen plaats in de gekrompen energie-intensieve industrie in het ARRRA-gebied, en daarin voorzien kon worden door een behoorlijk aanbod uit regionale productie naast kleine importvolumes. De waterstofwaardeketens waren weinig divers en de innovatie in (groene) sleuteltechnologieën voor waterstof was ontoereikend. Het streven naar duurzaamheid tegen elke prijs resulteerde in exact dat, een hoge prijs. Energiezekerheid en betaalbaarheid bleven hierdoor onder de maat tot 2040. Uiteindelijk bleek de periode toch een opmaat naar klimaatneutraliteit in 2050, maar dit kwam vooral door de verdere teloorgang van de Europese industriële basis.

STRATEGISCHE OPTIES VOOR DE VERSTERKING VAN HET ROTTERDAMS HAVEN-INDUSTRIEEL CLUSTER

De vier scenario's schetsen een aantal zekerheden en onzekerheden in ontwikkeling van een waterstofmarkt. Daaruit kunnen vijf scenario-ontstijgende strategieën worden geformuleerd om zorgen te adresseren die ontstaan uit de meeste scenario's. Dit zijn de meer robuuste 'no-brainers' die de actoren in het haven-industrieel cluster kunnen inzetten. Er zijn ook drie scenario-specifieke strategieën die alleen werken in twee van de vier scenario's en die daarmee risicovoller zijn.

Navolging geven aan deze strategieën vraagt een actieve inspanning van verschillende betrokkenen. Coördinatie, zo niet samenwerking, is de sleutel voor een duurzame ontwikkeling van het cluster in een steeds onzekerdere wereld.

SCENARIO-OVERSTIJGENDE STRATEGIEËN

1. **Breid regionale productie van duurzame elektriciteit en waterstof substantieel uit**: alle scenario's onderstrepen dat energievoorzieningszekerheid niet langer als vanzelfsprekend beschouwd kan worden. Dit maakt investeringen noodzakelijk in de productie van elektriciteit en waterstof, ook al is de ruimte

beperkt en bestaat het risico dat toename van het gebruik van waterstof beperkt zal blijven. Verticale integratie van waterstofproductie, met langdurige afnameovereenkomsten, neemt een aantal risico's tot op zekere hoogte weg.

2. **Diversifieer importen naar aanbieders, energiebronnen, en -dragers**: toenemende geopolitieke en handelsbarrières vergroten de kans dat energiestromen verstoort raken en dat eigendommen en investeringen in het buitenland stranden. Voor toekomstige gebruikers van waterstof, zoals de chemie-, staal-, raffinage-, en transportsector, is de diversificatie van de aanvoer essentieel. De scenario's onderstrepen dat investeringen in het Atlantische bassin en Zuid-Europa robuuster zijn. Het Midden-Oosten en Noord-Afrika kunnen risicovoller zijn. Maar als de-globalisering intensifieert, dan kan deze regio een belangrijke export-hub naar Europa zijn. Het moet dan ook een punt van aandacht zijn voor Europese energie- en klimaatdiplomatie.

3. **Investeer in optionaliteit en multifunctionaliteit van terminals, conversiefabrieken, opslagfaciliteiten, infrastructuur en apparatuur**: in de energietransitie bestaat er niet één enkele oplossing voor alle vraagstukken. De partijen in het Rotterdamse cluster kunnen dan ook beter niet al hun eieren in één mandje leggen. Gebruikers van waterstof kunnen streven naar het realiseren van optionaliteit door het aangaan van flexibele afnameovereenkomsten. Netbeheerders kunnen bijdragen aan optionaliteit middels de inzet op multifunctionele en multidirectionele infrastructuur, bijvoorbeeld door de aanpassing van gaspijpleidingen voor het transport van waterstof, maar ook voor andere gassamenstellingen zoals methaan, waterstofsulfide en ammonia. Ook andere, bestaande infrastructuur voor fossiele brandstoffen, zoals LNG-terminals, moet geschikt gemaakt worden voor ammonia en andere waterstofderivaten zonder daarbij het gebruik van fossiele brandstof onnodig te verlengen.

4. **Investeer in back-up en vluchtstroken in waterstofproductie, conversie-, opslag-, en infrastructuurcapaciteit**: optionaliteit moet worden aangevuld met andere ogenschijnlijk redundante elementen in het energiesysteem, zoals back-up elektriciteitsproductiecapaciteit, strategische energievoorraden en pijpleidingen die maar zelden op volle capaciteit benut zullen worden. 'Redundantie' wordt al snel als kostbaar gezien, maar de optiewaarde ervan moet ook onderkend worden. Deze waarde moet een plek krijgen in processen die leiden tot investeringsbeslissingen.

5. **Zet nog harder in op circulariteit**: terwijl het al vorm begint te krijgen, kan een sterkere inzet op circulariteit een aantal externe (energie-)afhankelijkheden

verder wegnemen. Dit kan door het aantrekken van nieuwe ondernemingen en aanbieders van diensten, en door co-investeringen in haveninfrastructuur die nodig is voor het transport en de opslag van materialen, moleculen, en energie in het cluster. Havenbedrijf Rotterdam kan kennisdeling ondersteunen, bijvoorbeeld met betrekking tot verbetering van verkrijgen, sorteren, en verwerken voor schaarse materialen zoals platina, en het opschalen van innovaties voorbij de pilot fase. Circulariteit zal echter ook nieuwe wederzijdse fysieke en relationele afhankelijkheden creëren.

SCENARIO-SPECIFIEKE STRATEGIEËN

6. **Vervang huidige grijze waterstof met koolstofarme waterstof en omarm de transitie in andere industriële segmenten**: het vervangen van het huidige gebruik van grijze waterstof in de chemische industrie is een *low-regret* maatregel. Het kan dienen als een belangrijk signaal en het pad effenen voor het gebruik van koolstofarme waterstof in andere sectoren. Het is bovendien een betekenisvolle boodschap aan overheden en de maatschappij dat de sector de energietransitie omarmt als een proactieve, in plaats van regulering-volgende partij. Dit is belangrijk, aangezien geen van de scenario's een maatschappelijke en politieke *licence-to-operate* garandeert voor de grote (chemische) industrie in het ARRRA-gebied.

7. **Schaal de investeringen in aanvoer van strategische transitiegrondstoffen op en geef vorm aan beheersing van aanvoerketens**: een waterstoftransitie vereist een voldoende beschikbaarheid en betaalbaarheid van strategische transitiematerialen, technologieën, en goed opgeleid personeel. In *Het Gelijk van Sun Tzu* en in *Verwoeste Bruggen* moeten de overheden in Noordwest-Europa diplomatieke inspanningen opvoeren, en investeren in de handelsrelaties met producenten van kritische grondstoffen. Tegelijkertijd moeten overheden beginnen met het monitoren van de behoefte aan materialen en technologie in het ARRRA-gebied en van import-afhankelijkheden. Hier kan worden voortgebouwd op de kracht van Noordwest-Europa, met het prioriteren van innovatieprogramma's rond volgende-generaties materialen, schone technologieën. Regulering die (voortijdige) overname verhindert van strategische ondernemingen kan daarbij nodig blijken. Een prominente veiligheidscomponent in het industriebeleid kan essentieel zijn, waarbij de stabiliteit van het beleid gewaarborgd moet zijn. Deze strategie kent risico's en is geen vereiste in alle scenario's. Protectionisme is maatschappelijk kostbaar, zeker indien kosten veelal gesocialiseerd worden terwijl de opbrengsten privaat zijn. Het overeind houden van mogelijk inefficiënte industrieën zal vragen oproepen.

8. **Werk samen met andere havens in het ARRRA-gebied in de import van en handel in waterstof en waterstofderivaten**: de energietransitie is een uitdaging die te groot is voor één individueel haven-industrieel cluster. In *Het Gelijk van Sun Tzu* en in *Europa's Eureka*, maar ook gegeven de mogelijkheid van frequente verstoringen en veranderingen van de aanvoerlijnen, kan nauwere samenwerking de weerbaarheid, veerkracht, en het aanpassingsvermogen in het ARRRA-gebied en het achterland verhogen. Dit vraagt informatie-uitwisseling en coördinatie in de adoptie, uitrol en opschaling van nieuwe technologie. Het zou een bepaalde mate van intraregionale havenspecialisatie vragen, waarbij de Rotterdamse Haven bijvoorbeeld haar nabijheid tot ondergrondse opslag van waterstof en CO_2-afvang en opslag benut.

INTRODUCTION

The Russian invasion of Ukraine in February 2022 and resulting Western sanctions against Russia have yet again brought the inherent interconnectedness between geopolitics and energy to the forefront of the public debate. The current global energy crisis has reiterated that geopolitical and societal dynamics have an immense influence on energy systems, and consequently, the energy transition. As is now evident, decades of European energy policy and, by implication, societal stability across Europe, was upended in a few months with possibly far-reaching consequences.

Thinking beyond current and past trends and near-term developments is more important than ever. This is particularly important in the energy sector, where high capital investments and long lead times necessitate robust long-term planning. Moving from the COVID-19 pandemic to the current energy crisis, the world is unevenly preparing for another crisis: a much slower unfolding climate crisis. Transforming the energy system while minimising disruption is proving a difficult task. Hydrogen is already a part of this transformation, but its exact role in the future system remains unclear.

LOW-CARBON HYDROGEN IN THE NEW ENERGY SYSTEM

Hydrogen is emerging as one of the key components of the energy and feedstock transition.[2] It already has a variety of industrial uses, but its role in future energy systems remains contested. Currently, the approximately 70 million tonnes (Mt) of annual pure hydrogen demand (of the total 94 Mt of hydrogen demand) is almost entirely derived from fossil fuels, which forms 6% of global natural gas and 2% of global coal consumption.[3] Hydrogen is expected to make only a modest contribution to the future energy system. However, geographic concentration of hydrogen use means that its role will be particularly pronounced in certain parts of the world. While both hydrogen use and its production can be emission-free, this is currently far from reality. How quickly low-carbon hydrogen can be introduced at scale is subject not only to economic and technological variables, but also to geopolitical and societal factors.

2 International Energy Agency, 2022. *Global Hydrogen Review 2022*, p. 12. https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

3 Global Hydrogen Review 2022, p. 5; International Energy Agency, 2019. *The Future of Hydrogen*, p. 17. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

Low-carbon hydrogen definition	For hydrogen to qualify as 'low-carbon', 'grey' hydrogen production from conventional fossil-based sources has to be coupled with carbon capture, utilisation or storage (CCUS) to produce 'blue hydrogen'.[4] The EU takes this approach, and defines low-carbon hydrogen as *'hydrogen the energy content of which is derived from non-renewable sources, which meets a greenhouse gas emission reduction threshold of 70%.'*[5] Other bodies, such as the UK government, consider low-carbon hydrogen to be hydrogen produced with greenhouse gas (GHG) emissions of under 20 gCO_2e, without specifying its origin.[6] This report considers all forms of hydrogen produced with minimal CO_2 emissions, in line with this standard, to be low-carbon hydrogen. This encompasses various forms of hydrogen likely to make up future value chains.

EXPLORING PATHWAYS THROUGH SCENARIOS

Coherent narratives about what future geopolitical and societal dynamics might look like can help understand how hydrogen value chains and trade networks will emerge in uncertain and complex situations. This project therefore created scenarios **so companies, governments and business networks can develop strategies to robustly position themselves in future low-carbon hydrogen value chains and markets**. This project addresses the implications for the Amsterdam-Rotterdam-Rhine-Ruhr-Antwerp (ARRRA) region, but derives strategic recommendations specifically for stakeholders active in the Rotterdam port-industrial cluster.

The scenarios illustrate four different, yet all possible, global systems that could shape the emergence of distinctive hydrogen value chains into the ARRRA region. These scenarios are situated in the 2040s and look back at the developments leading to the situation that the world and the ARRRA cluster are in . They form the basis for

4 Ochu, E., Braverman, S., Smith G., Friedman J., 17 June, 2021. *Hydrogen Fact Sheet: Production of Low-Carbon Hydrogen*. Columbia Center on Global Energy Policy. https://www.energypolicy.columbia.edu/research/article/hydrogen-fact-sheet-production-low-carbon-hydrogen.

5 European Commission, 15 December, 2021. *Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen*, p. 51. https://eur-lex.europa.eu/resource.html?uri=cellar:2f4f56d6-5d9d-11ec-9c6c-01aa75ed71a1.0001.02/DOC_1&format=PDF.

6 UK Department for Business, Energy & Industrial Strategy, 2022. *UK Low Carbon Hydrogen Standard*, p. 3. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092809/low-carbon-hydrogen-standard-guidance-v2.1.pdf.

implications and strategic recommendations that are derived. They also form the early indicators presented to improve making sense of the direction in which the global system is headed.

This report focuses on the future of low-carbon hydrogen in the ARRRA region in general and the Rotterdam port-industrial cluster in particular. It is intended for actors in the emerging low-carbon hydrogen value chain, particularly in north-west Europe. Those engaged in other (energy) sectors or subsectors influenced by geopolitics may also find the scenarios useful.

This report is structured as follows:

- Chapters 2-5 explain the process behind the scenarios and their implications;
- Chapter 6 describes the actual scenarios;
- Chapters 7-9 explain the implications and strategic options for stakeholders in the Rotterdam port-industrial cluster.

1 SCENARIO PLANNING METHODOLOGY

Anticipating and adapting to uncertainties in the future requires a suitable method of analysis. This research is based on **scenario planning**: a '*disciplined method for imagining possible futures*' that '*simplifies the avalanche of data into a limited number of possible states*.'[7] Scenario planning is designed to challenge conventional thinking about trends, dynamics and pathways in established systems, and to understand how deviations from current pathways can drastically reshape an organisation, a system or another unit of analysis. Although it involves some rigorous methodological steps, scenario planning is more an art than a science. It acknowledges that much of the future is unpredictable and that actors need to use their imagination to strategically prepare for the unforeseeable. In comparison with more deterministic approaches such as forecasting, scenario planning helps to effectively account for uncertainty in strategic planning and to communicate it clearly.

Scenario planning involves creating and analysing scenarios to draw implications, strategic options and early indicators for tracking developments associated with a focal issue. While the concept and use of scenarios goes back to ancient history, it re-emerged in a more sophisticated form in the 1950s at the RAND Corporation, and was popularised in commercial use after Shell embraced the methodology in the early 1970s.[8]

Scenario planning is now applied in research and practice, across business, finance, as well as in military and intelligence settings.[9] Due to this range of applications, various methodologies have emerged over time. While this variability is a point of contention in academic circles, the outer boundaries of what scenario planning entails, and its benefits, are well established.[10]

7 Schoemaker, P., 1995. *Scenario Planning: A Tool for Strategic Thinking*. MIT Sloan Management Review, pp. 25-26. https://enlazate.kuikmatch.com/wp-content/uploads/sites/19/2021/06/Scenario-Planning-2.pdf.

8 Bradfield. R., Wright, G., Burt, G., Cairns, G., van der Heijden, K., October, 2005. *The origins and evolution of scenario techniques in long range business planning*. Futures. https://www.sciencedirect.com/science/article/pii/S0016328705000042.

9 Bradfield et al., *The origins and evolution of scenario techniques in long range business planning*.

10 Spaniol, M., Rowland, N., January, 2018. *The scenario planning paradox*. Futures. https://www.sciencedirect.com/science/article/pii/S0016328717302537; Schoemaker, P., March, 1993. *Multiple scenario development: Its conceptual and behavioral foundation*. Strategic Management Journal. https://onlinelibrary.wiley.com/doi/10.1002/smj.4250140304; Schoemaker, *Scenario Planning: A Tool for Strategic Thinking*, p. 37.

Using scenarios is also quite common in the energy sector. Numerous scenario models have been created by organisations such as the IEA and Hydrogen Europe to sketch a variety of emerging and expanding value chains such as those for hydrogen. However, most scenarios focus on quantitative modelling, therefore biassing them towards quantifiable metrics, such as costs and technical parameters, while omitting the impact of qualitative variables such as geopolitics, institutions, and society. As such, this report's qualitative approach to scenario planning addresses this gap by bringing these overlooked elements to the forefront.

This research combines the scenario planning process with academic theories on energy security, political economy, institutional and evolutionary economics, complexity theory, commodity trade, transition and transition management, as well as geopolitics. Some theories are applied more or less directly, while others inspire particular aspects of the process. The grounding in academic theories provides a coherent framework for understanding the implications of these versions of the future. This is substantiated by primary research of a variety of written materials and using 20 expert interviews and four focus group discussions in stakeholder meetings.

This research draws upon the 8-step process used by Stratfor, presented in Figure 1 below.[11]

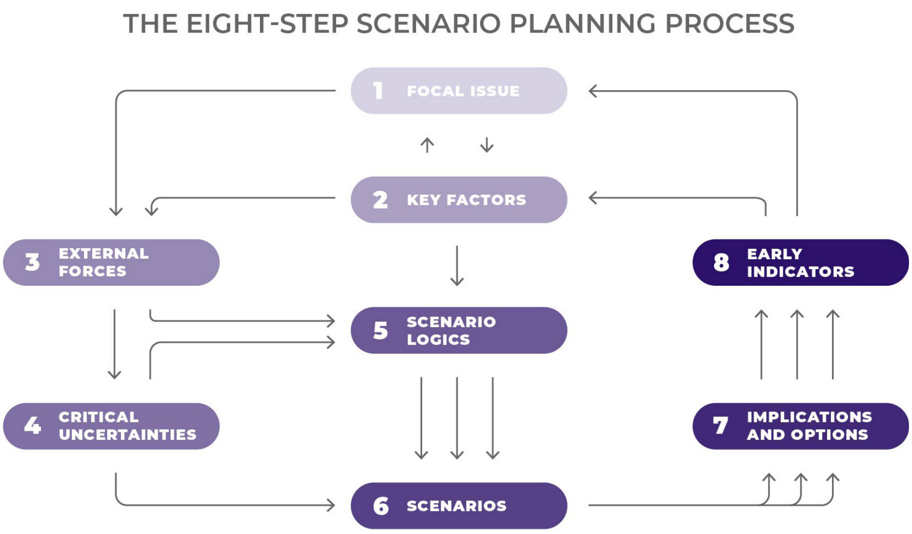


FIGURE 1. THE EIGHT-STEP SCENARIO PLANNING PROCESS[12]

11 Ogilvy, J., 2015. *Scenario Planning and Strategic Forecasting*. Stratfor. https://worldview.stratfor.com/article/scenario-planning-and-strategic-forecasting.

12 Image credit: boerenjongens; adapted from Ogilvy, J., *Scenario Planning and Strategic Forecasting*.

EIGHT DISCRETE STEPS

Step 1, defines the focal issue, identifying **what is at stake**, **for whom**, and **in which time horizon**. This step focuses the research on the ARRRA supercluster, and the Rotterdam port-industrial cluster as the primary unit of analysis in this study.[13]

Step 2, **identifies key actors** and **key factors** that shape the development paths of low-carbon hydrogen value chains in the ARRRA region. This includes specific industrial markets for hydrogen, namely steel, chemicals and marine transportation.

Step 3 **maps out the key external social, economic, environmental, political and technological (SEEPT) forces** that will shape the development paths of hydrogen value chains along the spectrum of local to global levels. This step draws on previous research and articles published by the research team,[14] a systemic desk analysis of 26 studies (see Appendix II), and a set of ten expert interviews conducted in Step 3 to validate the research team's selection of forces.[15] The selection and analysis of SEEPT forces yielded 30 possible forces with a total of 104 subthemes. Through a filtration process within the expert interviews and research team, 20 SEEPT forces were selected for use in the scenarios. The filtration process focused on the proximity of the individual forces to the focal issue, the importance attributed to the force in the literature and interviews, and the force's ability to serve as an opportunity and a threat to the focal issue.

Step 4, in contrast to the divergent thinking in Step 3, uses a convergent process of prioritisation to **define the critical uncertainties** from the SEEPT forces. Using the Wilson Matrix and Cross-Impact Analysis the research team selected a set of forces with the highest degree of uncertainty, the highest impact on the focal issue, and substantial impact on the other forces, to underpin the scenario logic. By having experts rank the 20 forces against their potential impact and the likelihood that they develop into a significant issue, the Wilson Matrix prioritises the influence and

13 For this report, Port of Rotterdam Authority refers to the organisation responsible for the management of the Port of Rotterdam, while the Rotterdam port-industrial cluster refers to the port and industrial activities based within or near the territory managed by the Port of Rotterdam Authority.

14 Clingendael International Energy Programme, January 2004. *Study EU Energy Supply Security and Geopolitics*. https://www.clingendaelenergy.com/publications/publication/study-eu-energy-supply-security-and-geopolitics; Notermans, I., van de Lindt, M., van der Have, C., van Raak, R., Rotmans, J., 2020. *Hydrogen for the Port of Rotterdam in an International Context - a Plea for Leadership*. Drift. https://drift.eur.nl/app/uploads/2020/06/KSD_DRIFT_HavenbedrijfRotterdam_vDEF_lores.pdf; International Energy Agency and Clingendael International Energy Programme, April 2021. *Hydrogen in North-Western Europe, a vision towards 2030*. https://www.clingendaelenergy.com/publications/publication/hydrogen-in-north-western-europe-a-vision-towards-2030.

15 The expert interviews consisted of two independent senior energy experts and eight expert interviews with research project stakeholders.

uncertainty of each scenario force selected above.[16] The rankings of the eight experts involved were averaged to determine the critical uncertainties.

Building on the Wilson Matrix, the Cross-Impact Analysis looks at a force in the context of the likelihood of other forces occurring, so each force is not observed in isolation.[17] Experts rank how likely a force will occur within a given time period, and then rank how likely it is to happen given the occurrence of another force. In this project, data from eight entries was aggregated, then averaged and ranked, to show the consensus scores and the outlier scores.

Step 5 uses the outputs from the previous step to **formulate a scenario logic** through a morphological analysis. The morphological analysis is '*a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes*'.[18] This sketches out scenario frameworks, based on various combinations of the different critical uncertainty outcomes.

Step 6 is the actual **scenario writing**. The scenarios are narratives capturing trends, events, protagonists and historical analogies. The four scenarios create more extreme but plausible, divergent worlds to challenge strategic thinking about how alternative geopolitical developments can alter the development of hydrogen trade and supply networks.

Step 7 brings together all previous steps to **identify the implications of the scenarios** and **the strategic options most suitable to address those implications**. Some options are scenario specific, while others apply to multiple scenarios. This step draws on the Product Life Cycle Theory (also known as the Dynamic Market Theory), the Resource-based view of Economics, Transaction Cost Economics, Complexity Theory and Transition Management to systematically anticipate possible hydrogen market developments from the four scenarios, including what these developments might imply for future participants in these markets.[19]

16 Amer, M., Daim, T., Jetter, A., February, 2013. *A review of scenario planning*. Futures. https://www.sciencedirect.com/science/article/pii/S0016328712001978.

17 Schaars, S., February, 1987. *How to develop and use scenarios*. Long Range Planning, p. 111. https://www.sciencedirect.com/science/article/pii/0024630187900380.

18 Ritchey, T., 2013. *General Morphological Analysis*. Swedish Morphological Society. https://www.swemorph.com/ma.html.

19 Williamson, O., 2008. *Transaction Cost Economics*. Handbook of New Institutional Economics, pp. 41-65. https://link.springer.com/chapter/10.1007/978-3-540-69305-5_4; Lockett, A., Thompson, S., November-December 2001. *The resources-based view and economics*. Journal of Management. https://www.sciencedirect.com/science/article/pii/S0149206301001210; H. W. de Jong, Dynamische Markttheorie, Stenfert Kroese, 1981.

Similar to Step 3, ten experts were consulted to validate the implications identified by the research team.

Step 8 concludes the process by **establishing early indicators that can be tracked to anticipate major changes** and shift the course from one scenario in favour of another.

SCENARIO PLANNING ADVANTAGES

The scenario planning method naturally allows for adaptation, as the methodological steps are not specifically defined. After input from research team members and external actors, such as the project stakeholder group, the research team was able to iterate each step. A number of steps were adapted to tailor the methodology to work for a research consortium, rather than a single party, with the unit of analysis, the Rotterdam port-industrial cluster, being multiple actors, rather than a single principal. This particularly affected the approach to the Cross-Impact Analysis in Step 4 and to identifying implications and options in Step 8. In Step 4, the team averaged and ranked the values generated in the Cross-Impact Analysis to identify common and outlier forces.

2 FOCAL ISSUE

Hydrocarbons such as oil, gas and coal, and their derivatives, are the lifeline of today's north-west European economy.[20] Hydrocarbons are consumed by industrial and commercial sectors, and households, either directly, or indirectly through electricity, in the form of energy and products. The Port of Rotterdam is the leading energy and resource port in Europe, and an array of commercial actors involved in and around the hydrocarbon supply chain are established in the port-industrial cluster and the wider Amsterdam-Rotterdam-Antwerp (ARA) region. These connect to the Rhine-Ruhr region and the Chemelot industrial cluster, to form the ARRRA industrial supercluster. In this, the Rotterdam port-industrial cluster's role is key, as it serves as a hub for hydrocarbon distribution to the rest of the ARRRA region.

FIGURE 2. MAP OF THE ARRRA SUPERCLUSTER IN THE GLOBAL CONTEXT

This economic context is now meshing with national and supranational climate policies that will drastically reshape the hydrocarbon value chain and stimulate the emergence of new value chains. Hydrogen already plays a key role in the industrial landscape of Rotterdam and the wider ARRRA region. North-west Europe is responsible for 5% of global hydrogen demand and 60% of total European demand, with Germany and the Netherlands being the largest markets within the region.[21] Current demand is mostly concentrated in petrochemical refining and ammonia production for fertilisers. Low-carbon hydrogen could contribute to reducing emissions from current hydrogen use and to substituting hydrocarbons currently consumed, particularly in the steel and chemical sectors.[22]

20 North-west Europe in the context of this paper refers to Belgium, Denmark, France, Germany, the Netherlands, Norway and the UK.

21 IEA and CIEP, 2021. *Hydrogen in North-Western Europe, a vision towards 2030*, p. 5.

22 Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 4.1, 2021.

Hydrogen has been used in the Rotterdam petrochemical cluster for decades. 96% of all hydrogen produced in north-west Europe is based on fossil fuels.[23] Currently, it is mainly produced from natural gas and residual gases using steam methane reforming. Conversion to low-carbon hydrogen requires not only a change in policy, but a systemic shift in how hydrogen is produced, transported and used within the system. The limited land space available in the Netherlands to produce renewable energy by means of electrolysis, necessitates hydrogen imports.[24] Which hydrogen carriers (liquified hydrogen, liquid organic hydrogen carriers, ammonia, methanol or others) and on which timeline, will emerge as the primary transport modes are not yet evident. Some market players have already signalled a preference for shipping ammonia, which would also mean adapting and expanding existing value chains.[25]

The European Union has now put hydrogen firmly in its sights, particularly spurred on by the ongoing energy crisis. The EU has adopted directives to stimulate hydrogen use, has expressed intent to establish a European Hydrogen Bank to guarantee demand, and has been finetuning its hydrogen policies to accommodate the requests from market players, for example by repealing the additionality clause for hydrogen producers.[26] In addition to EU efforts, Germany has already engaged in proactive bilateral diplomacy to secure hydrogen imports for the domestic market, for example, by setting up the H2Global Initiative.[27] This highlights cooperation and competition in the race to establish and expand low-carbon hydrogen value chains in north-west Europe.

23 IEA and CIEP, 2021. *Hydrogen in North-Western Europe, a vision towards 2030*, p. 6.

24 Notermans et al., *Hydrogen for the Port of Rotterdam in an International Context - a Plea for Leadership*, p.13

25 Parkes, R., 25 May, 2022. *Commoditising hydrogen; International trading of green ammonia could begin as soon as 2025: Trafigura*. Recharge News. https://www.rechargenews.com/energy-transition/commoditising-hydrogen-international-trading-of-green-ammonia-could-begin-as-soon-as-2025-trafigura/2-1-1225219.

26 Wilson, A., March 2022. *EU directive on gas and hydrogen networks*. Briefing, first edition, European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729303/EPRS_BRI(2022)729303_EN.pdf; Parkes, R., 14 September, 2022. *'From niche to scale'; EU launches €3 bn European Hydrogen Bank with a bang but keeps quiet about the details*. Recharge News. https://www.rechargenews.com/energy-transition/from-niche-to-scale-eu-launches-3bn-european-hydrogen-bank-with-a-bang-but-keeps-quiet-about-the-details/2-1-1299131; Parkes, R., 14 September, 2022. *Scrapped; EU's controversial 'additionality' rules for green hydrogen are history after European Parliament vote*. Recharge News.
https://www.rechargenews.com/energy-transition/scrapped-eus-controversial-additionality-rules-for-green-hydrogen-are-history-after-european-parliament-vote/2-1-1299195.

27 German Federal Foreign Office, 27 February 2022. *Hydrogen diplomacy office opening in Saudi Arabia*. https://www.auswaertiges-amt.de/en/aussenpolitik/themen/hydrogen-diplomacy-office/2513802; Argus Media, 13 October, 2022. *First auction for renewable fuels imminent: H2Global*. https://www.argusmedia.com/en/news/2380161-first-auction-for-renewable-fuels-imminent-h2global.

New value chains are evolving. Not only as part of a complex energy transition – a shift away from fossil-based energy production and consumption to renewables – but also in an uncertain geopolitical and societal landscape. This is materialising in the middle of the energy and cost of living crisis, precipitated by the COVID-19 pandemic, and by Russia's invasion of Ukraine including the sanctions regime that followed. While some developments have more deterministic outcomes, such as the damage to the Nord Stream 1 and 2 pipelines guaranteeing that natural gas flows via 40% of pipeline capacity between Russia and the EU will not resume in the medium term, the implications of other dynamics are less clear.[28] Russia, formerly Europe's key energy partner, is now the world's most sanctioned nation, and the EU continues to tighten sanctions.[29]

Given the fallout from the military, energy and cost of living crises, in an environment of global strategic competition, the future of EU-Russia (energy) relations, and the EU's energy transition ambitions, the emergence of low-carbon hydrogen value chains is unpredictable. Based on this set of complex issues, the following questions underpin the focal issue of this research:

How will geopolitics shape the emergence of hydrogen trade and supply networks into the ARRRA supercluster and what effect will this have on key actors and on Dutch society in the period between 2025 and 2040?

28 Van der Linde, C., 6 October, 2022. *Verdwenen Opties*. Energiepodium. https://www.clingendaelenergy.com/inc/upload/files/Verdwenen-Opties.pdf.

29 Wadhams, N., 7 March, 2022. *Russia is Now the World's Most-Sanctioned Nation.* Bloomberg. https://www.bloomberg.com/news/articles/2022-03-07/russia-surges-past-iran-to-become-world-s-most-sanctioned-nation.

3 KEY ACTORS AND KEY FACTORS

The previous chapters define the time horizon and what is at stake. In this chapter, the key actors and key factors interacting with the focal issue are introduced. The key actors identified are:

- National government of the Netherlands
- Port of Rotterdam Authority
- Trading companies active in the Rotterdam port-industrial cluster
- Industrial and energy companies active in the Rotterdam port-industrial cluster

These actors have been selected to link the implications of global dynamics and their interaction with the ARRRA supercluster to the actors most connected with the focal issue in the Rotterdam port-industrial cluster. The national government of the Netherlands was selected over other tiers of government, because of its role in translating and applying EU regulations at the member state level.[30] These key actors interact with various factors that shape the development paths of hydrogen value chains in north-west Europe. While the individual role of each actor is important, this research aggregates the actors into a port-industrial cluster 'ecosystem' to better address the spatial, temporal and thematic breadth of this report. The following chapter introduces the exogenous forces that underpin the scenarios. These forces are presented in Table 1 below:

30 The policies of German state governments, particularly North Rhine-Westphalia, can also be considered influential in this context, but were outside of the scope of this research.

'Hardware' factors	'Software' factors
Infrastructure	**Supply and demand**
Dedicated hydrogen pipelines[31]	Product diversity and asset specificity
Electricity grid expansion	Market participants and their behaviour
Carbon capture, utilisation or storage (CCUS) facilities	Types and frequency of transactions
Hydrogen storage and processing facilities	**Presence of international commodity flows** in hydrogen and derivatives, with an existing bunker market in Rotterdam and a pricing centre for other commodities, thus already providing important related services.
Port infrastructure	**Mechanisms for price discovery**, particularly in light of current discussion on price caps of Russian energy carriers, and the EU's aim of purchasing natural gas as a monopsony.
Competing and complementing developments with other regional ports and industries. For example the Green Energy Hub recently created by TES in the German port of Wilhelmshaven.[32] Now that piped imports from Russia have been cut off, ports on the north-west Europe shoreline will become more important. However, major ports such as Rotterdam will face increased competition from smaller ports such as Wilhelmshaven and Eemshaven.	
Technology	**Institutions**
Innovation in electrolysis technology in terms of scale, efficiency and functionality.	**Market structures** which will evolve as the market develops. For example, initial long-term contracts transitioning towards spot market trading as excess volumes begin to change hands at large storage hubs.
Innovation in fuel cell technology and efficiency.	**Organisational formats** of critical assets and markets in different phases of development, particularly as countries choose whether to serve domestic demand or export. Exemplified by China's decision to export additional refined oil products, and processing and refining of critical raw materials, which are also highly concentrated in China.[33]
Innovation in hydrogen storage.	**Rules and regulations** concerning production, transport, use and trade of hydrogen, such as applying the EU Renewable Energy Directives,[34] as well as tradable (environmental) permits and non-tradable tariffs and regulations.[35]
Availability and affordability of critical technology.	Norms and standards.
	Market interventions such as incentives and support to pilot schemes to shift green hydrogen production from double-digit megawatt scales, to triple megawatt and single-digit gigawatt scales. In the Netherlands, the government is also facilitating demand creation. Together, these efforts stimulate learning curves, particularly in electrolyser capacity.

TABLE 1. KEY FACTORS WITH WHICH KEY ACTORS INTERACT

31 Infrastructure-related developments such as Gasunie's preparedness to refurbish natural gas pipelines for hydrogen (HyWay 27) and the Regionale Energie Strategie (RES). Gasunie, 30 June, 2021. *Gasunie: decision on hydrogen infrastructure is milestone for energy transition*. https://www.gasunie.nl/en/news/gasunie-decision-on-hydrogen-infrastructure-is-milestone-for-energy-transition; Regionale Energie Strategie, n.d. https://www.regionale-energiestrategie.nl/home/default.aspx.

32 TES, n.d. *Wilhelmshaven Green Energy Hub*. https://tes-h2.com/wilhelmshaven-green-energy-hub/.

33 Tan, F., Xu, M., 3 October, 2022. *China sets oil products export quotas at about 15 million tonnes*. Reuters. https://www.reuters.com/business/energy/china-sets-oil-products-export-quotas-about-15-mln-t-sources-2022-09-30/.

34 European Commission, n.d. *Renewable Energy - Recast to 2030 (RED II)*. https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en; Messad, P., 14 September, 2022. *European Parliament backs 45% renewable energy goal for 2030*. Euractiv. https://www.euractiv.com/section/energy-environment/news/european-parliament-to-adopt-a-45-renewable-energy-goal-for-2030/.

35 See CIEP, Managing Future Security of Low Carbon Hydrogen Supply, 2022. Protectionist policies aimed at stimulating the domestic value chain will influence the traders' ability to sell hydrogen (derivatives) in the respective market. For example, hydrogen being included in the EU's carbon border adjustment mechanism.

4 ANALYSIS OF SEEPT FORCES

The 20 forces selected to underpin the scenario narratives are divided into five categories: Social Economic, Environmental, Political and Technological (SEEPT) and are presented in the table below. The selection process captures the diversity of developments in different domains that may significantly shape the emergence of the low-carbon hydrogen value chain. The forces selected include those frequently referenced in the literature and interviews, as well as issues discussed less frequently, but which will nonetheless have critical second and third order implications for the value chains. All the selected forces are formulated to balance interpretability and specificity to the hydrogen and ARRRA use cases.

Industry scenarios and market projections typically overemphasise measurable and quantifiable metrics – usually economic or technological. Social structure or the level of global political cohesion can have an equally high impact, but cannot be represented as easily. This research strives to address this by applying the 20 forces presented in Table 2 below, as the most significant exogenous (geopolitical) forces driving development of low-carbon hydrogen supply and trade networks in the ARRRA region.

Social	Economic	Environmental	Political	Technological
S1: Social structure	**EC1**: CO_2 abatement policies	**ENV1**: Climate change-induced extreme weather events	**P1**: Leadership in hydrogen and hydrogen technology development	**T1**: Learning curve for non-H_2 electricity storage
S2: Public acceptance of the energy transition	**EC2**: Stability of global financial markets	**ENV2**: Scarcity of raw materials	**P2**: Degree of global cohesion	**T2**: Access to key hydrogen technologies
S3: Energy (distribution) justice	**EC3**: Extent of globalisation	**ENV3**: Land and water availability	**P3**: Rules setters in global markets	**T3**: Emergence of intercontinental energy supergrids
S4: Availability of human capital	**EC4**: Industry relocation	**ENV4**: Sustainability pathways	**P4**: Energy security in north-west Europe	**T4**: Emergence of high-energy digital appliances

TABLE 2. OVERVIEW OF EXOGENOUS (GEOPOLITICAL) FORCES

In the following section, each force is defined, briefly introduced, and connected to the focal issue. Some forces do not have an evident first order effect on the emergence of low-carbon hydrogen value chains, but rather, they are structural drivers behind other developments that impact this process as second and third order effects.

SOCIAL FORCES

S1: Social structure

Definition: *The dominant socio-political approach to find solutions for issues in society at large, either in individualistic or collective solutions.*

The social structure in terms of individualism versus collectivism refers to '*the degree to which people in a society are integrated into groups*'.[36] In individualist societies people take care of themselves and their immediate surroundings, while in collectivist societies people are embedded in larger groups. Social structure indicates how groups within society organise themselves to address shared issues.

- In an individualistic society, the focus is on independence, individual rights, and freedoms. An individualistic society focuses on concerns and resources for finding solutions, and hence solution pathways can become pluriform and diverse.[37]
- In a collective society the focus is on group decisions, harmony and shared resources. It encompasses, a willingness to adopt decisions made by others, hence there will be less divergent opinions and a sole solution pathway.

In the hydrogen context, an **individualistic society** can be interpreted to have more trust in the market and commercial actors than in a central government to solve issues and distribute economic costs and benefits across society. It is more likely to leave value chain formation to market dynamics and competition. Emphasising individual solution pathways leads to more self-reliance and direct interpersonal relationships, self-sufficiency, energy independence and a focus on hydrogen solutions that serve the individual first. Diversity may lead to competitive advantages and global trade, but only when the local competition results in solutions that are competitive, also globally. Low-carbon hydrogen is currently not cost competitive, lacks key technologies, and requires high capital expenditure (capex) investments. Given the uncertainty in demand and value chain development, companies are unlikely to take the initiative and pursue this unilaterally.[38]

36 Hofstede, G., 2011. *Dimensionalizing cultures: The Hofstede model in context*. Online readings in psychology and culture, *2*(1), 2307-0919, p.11.

37 Hui, C. H., & Triandis, H. C., 1986. *Individualism-collectivism: A study of cross-cultural researchers*. Journal of cross-cultural psychology, 17(2), pp. 225-248.

38 Interview with a senior energy expert, March 2022.

On the contrary, in a **collective society** there is greater trust in finding collaborative approaches to problem solving. This includes socialising concentrated costs across the wider society and collectivised decision-making. Societal acceptance of some negative effects forced upon some for the greater good is typically higher if compensated, but there is also an expectation for collective compensation regarding negative effects from market forces. In the hydrogen context, this places greater emphasis on a central government to decide upon a solution pathway.

The demands of individual actors are weighted against the collective benefit. Markets are used to achieve the commonly set goals. Eventually, solutions are chosen that serve the collective as a whole:

- local production combined with a possible sacrifice of other local uses for the land and/or water;
- imported and possibly sacrificing affordability or energy dependence, to some extent.

S2: Public acceptance of the energy transition

Definition: *Extent of public acceptance of policies and practices aimed at promoting the transition from a fossil-fuel-based economy to a renewables-based, carbon-neutral economy.*

Public acceptance will depend extensively on the efforts made to distribute concentrated costs and benefits between different groups and actors. It also relates to the public's perception of a common transition goal: the extent to which some groups in society reject the link between fossil fuels and climate change, and risk perception (health, operational, environmental), especially regarding introducing new technologies. This will particularly be the case for hydrogen, which is currently not used extensively outside industrial applications and hydrogen carriers such as ammonia, which is hazardous because of its toxicity for humans.[39] In densely populated regions, such as north-west Europe, competing uses of land by different groups (e.g., households and industry around the Port of Rotterdam) can lead to a more contested introduction of hydrogen infrastructure. The current high level of attention in the EU being paid to geopolitical risks may increase societal acceptance of the energy transition – not based on sustainability, but on grounds of breaking energy dependence on Russia.

39 International Labour Organization, October 2013. *Ammonia Showcard*. https://www.ilo.org/dyn/icsc/showcard.display?p_lang=en&p_card_id=0414&p_version=2.

In the context where energy security and affordability have taken centre-stage, social perception of transition efforts (towards sustainability) is key. Lack of acceptance of the energy transition could lead to:

- local and national protests to stringent climate policy;
- contesting and setting limits to public spending on the energy transition;
- difficulties in increasing cost competitiveness of renewable alternatives to fossil fuels;
- failure to decarbonise high-emission sectors;
- limits to certain import routes;
- limits to subsidies (for certain parties);
- barriers to particular technologies (e.g., blue hydrogen or certain storage).

Protests may also concern the high costs of far-reaching electrification, in financial as well as non-financial terms (such as the impact on landscape), and possibly, the decrease in system reliability, and economic decline because of industrial relocation.

S3: Energy (distribution) justice

Definition: *The influence of equitable energy distribution (access) concerns when determining value chains and (hydrogen) energy system organisation.*

A just energy transition refers to a transition in which costs and benefits of energy are fairly spread (distributive justice), and in which diverse groups and their rights and access to energy are considered (justice through recognitions), and included in energy decision-making (procedural justice).[40] Justice issues increasingly influence energy relations at different scales and within different geographies. Globally, energy justice arguments are increasingly raised in Global North vs. Global South discussions on carbon reduction and economic development. This includes access to affordable fossil fuels for developing countries, who rely on such fuels for their economic development.[41] The energy transition risks raising the cost of living for communities that are unable to make the switch to another energy system and technologies such as hydrogen.

With regard to hydrogen, a key question is whether the current approach to value chain development, in which scarce materials and energy are oriented from the

40 Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R., 2016. *Energy justice: A conceptual review*. Energy Research & Social Science, 11, pp. 174-182.

41 Pilling, D., 1 June, 2022. *Can Africa grow without fossil fuels*? Financial Times. https://www.ft.com/content/1e8c12fe-4823-41a1-8069-b6150876427d.

South towards the North, is just. This particularly afflicts bilateral trade with future exporting countries, who often have no coherent plan to address domestic lack of access to electricity for a considerable part of their population, while exporting (new) energy resources abroad. An additional consideration is the potentially uneven impact of pollution from electricity generation, transport or use activities, particularly as countries seek to reduce their own emissions by offshoring polluting processes.[42]

In north-west Europe, distributive issues can emerge around the costs of infrastructure and who bears these costs. This will include access to hydrogen, the (perceived) societal legitimacy of users and uses of publicly subsidised hydrogen, as well as industry vs. society dynamics. A particular subtopic of distributive justice within industry is which sectors do or do not receive the scarce hydrogen, while waiting for the value chains to scale-up.

S4: Availability of human capital

Definition: *Availability of highly skilled and manual labour, for technology R&D, implementing hydrogen projects and associated infrastructure, and organisational governance and processes.*

Limitations in availability or skill level of personnel with local knowledge and capabilities in future production countries, including the shortage of workers with the required technical education in north-west Europe endangers the EU's ambitions in tech innovation and project realisation. Lack of highly skilled human capital leads to a slower roll out of hydrogen projects or slower progress in associated technology' learning. Alternatively, abundant human capital can reinforce early mover advantages on the global market by providing know-how to other markets, as Germany does in Nigeria and Saudi Arabia.[43]

This equally applies to the vocational workforce, for example in the Netherlands, where energy infrastructure and grid operators already face a shortage of technicians.[44] Human capital also extends to policymakers, who need to be capable of understanding what is happening in the changing (energy) system and respond

42 Hama, M., 24 August, 2022. *China throws Europe an energy lifeline with LNG resales*. Nikkei Asia. https://asia.nikkei.com/Politics/International-relations/Indo-Pacific/China-throws-Europe-an-energy-lifeline-with-LNG-resales.

43 German Federal Foreign Office. *Hydrogen diplomacy office opening in Saudi Arabia*.

44 Waarlo, N., 2 August, 2018. *Tekort aan technisch personeel staat ambitieus energietransitieplan in de weg*. de Volkskrant. https://www.volkskrant.nl/economie/tekort-aan-technisch-personeel-staat-ambitieus-energietransitieplan-in-de-weg~bfb3cd8a/; NOS, 5 December, 2021. *'Snelheid van energietransitie in gevaar door tekort aan technisch personeel'*. https://nos.nl/nieuwsuur/artikel/2408261-snelheid-van-energietransitie-in-gevaar-door-tekort-aan-technisch-personeel.

adequately to developments. Finally, the availability of human capital extends to wider demographic trends, the ageing population across Europe and other energy demand centres, such as South Korea and Japan, where without immigration, human capital shortages are likely to worsen, particularly for manual labour jobs which cannot be readily automated.[45]

ECONOMIC FORCES

EC1: CO_2 abatement policies

Definition: *Intra-EU and international alignment on CO_2 abatement policies and mechanisms.*

As hydrogen is now also included in the Carbon Border Adjustment Mechanism (CBAM), the EU's approach to certification, mandates/bans (e.g., emissions standards, forced closures), the emissions trading system (ETS) and the CBAM will influence emerging low-carbon hydrogen value chains. When higher CO_2 prices are introduced under emissions schemes, these will need to allow industries time to adjust their assets in line with their investment cycles.[46] The sensitivity of CO_2 price rises to the pace at which these parties can reasonably mitigate their GHGs, could lead to an increase in operational costs and a decrease in industry's ability to build up investment capacity for sustainability. The supply side may also be structurally constrained, leading to scarcity and high prices, some effects of which are already witnessed today, after a decade of limited oil and gas investment against a backdrop of divestment campaigns.

The EU has adopted a pragmatic approach to certification. Letting go of narrow sustainability definitions has allowed for trade in different sustainable energy carriers. The argument for this approach is that eliminating options, such as blue hydrogen, significantly reduces the flexibility of the energy system and options available.

1. Externally oriented measures such as CBAM could pressure fossil energy exporters to the EU, such as the Middle East, to decarbonise their supply or divert their supply to other markets.

45 United Nations Department of Economic and Social Affairs, 2022. *World Population Prospects 2022; Summary of Results*. https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022.

46 Clingendael International Energy Programme, October, 2019. *Van Onzichtbare naar meer zichtbare hand? Waterstof en Elektriciteit*. https://www.clingendaelenergy.com/publications/publication/van-onzichtbare-naar-meer-zichtbare-hand-waterstof-en-elektriciteit-.

2. Internally oriented measures, such as the ETS, could have convergent pricing mechanisms directing hydrogen development towards countries with natural cost advantages.

In contrast, in a setting with political pressure to realise hydrogen development, divergent pricing mechanisms would create distortions, enabling high-cost hydrogen industries to develop in locations where they would not naturally settle.

EC2: Stability of global financial markets

Definition: *Extent of stability versus volatility in global financial markets.*

Monetary economics, uncertain interest rates, and the re-emergence of the global debt crisis will affect financing costs. An unstable (low trust) society is less likely to produce institutions that keep financing costs low. Since economics and finance often follow geopolitical developments – governments and businesses alike will not make large, long-term investments regardless of profit without sufficient socio-political stability. A financial crash, such as that of 2008, would have an impact on the real estate market and subsequent energy demand. The impact of a global financial crisis can be expected to be uneven, based on a country's maturity and degree of interdependence, and also on its institutions and the strength of its currency.

Current market volatility comes atop high, and in some developed markets, still rising inflation rates, which differentiates it from the precursor to the 2008 global financial crisis. This adds pressure to financial market stability. Companies are therefore less likely to pursue higher risk and lower return capital-intensive projects such as hydrogen production and use, as these remain uncompetitive without sufficient government backing for project development.

Central bank interest rate hikes have become commonplace globally in 2022.[47] The US Federal Reserve increases have driven rates towards 2008 levels, ending more than a decade of low financing costs.[48] However, with persistent inflation and global growth slowdown, this assertive central bank policy adds uncertainty to financing costs, particularly in emerging industries where risks are high, such as the hydrogen value chain.

47 Russell, K., Smialek, J., 16 June 2022. *Interest Rates Rise Around the World, as War and High Inflation Grind On*. The New York Times. https://www.nytimes.com/interactive/2022/06/16/business/economy/global-interest-rate-increases.html.

48 Trading Economics, n.d. *United States Fed Funds Rate*. https://tradingeconomics.com/united-states/interest-rate.

EC3: Extent of globalisation

Definition: *Extent to which governments and companies interact and integrate in economies outside their domestic market, regional markets and the wider, global market.*

For several decades the world experienced an unprecedented period of global market liberalisation and international trade. The logic of efficiency and comparative advantages prevailed, and western multinationals first shifted manufacturing to China, and later to new emerging economies, such as Vietnam. However, in recent years, this process has stagnated and has even started to reverse. More companies are considering '*nearshoring, onshoring and reshoring*' their activities.[49] Fears of trade discontinuity due to geopolitical rifts, as exemplified by the US-China trade war, flared up since 2018 and were once again highlighted in 2022 by the US CHIPS and Science Act. This raises the risk for companies operating in foreign markets.[50]

Besides deglobalisation, reference is being made to 'regionalisation', whereby companies refocus on regional markets. This is particularly prominent in the EU, which is seeking to promote reshoring critical industries away from risky markets. For example, the EU's push for the European Battery Alliance for (electric vehicle) battery manufacturing and the European Chips Act for the semiconductor industry.[51] The logic of efficiency is being challenged by the desire to secure supply, and this will significantly influence how new value chains develop.

49 Wiggins, K., Gara, A., Smyth, J., 22 May, 2022. *Business leaders warn that three-decade era of globalisation is ending*. Financial Times. https://www.ft.com/content/0599878e-a820-4657-8e52-f069bb10d512.

50 Lo, K., 7 September 2022. *US Chips Act bars American companies in China from building 'advanced tech' factories for 10 years*. South China Morning Post. https://www.scmp.com/news/china/article/3191596/us-chips-act-bars-american-companies-china-building-advanced-tech.

51 European Battery Alliance, n.d. https://www.eba250.com/; European Commission, n.d. *European Chips Act*. https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en.

FIGURE 3. COMPARISON BETWEEN CHANGE IN GLOBAL VALUE OF EXPORTS (LEFT AXIS) AND SHARE OF MERCHANDISE TRADE AS % OF GLOBAL GDP (RIGHT AXIS). SOURCE: AUTHORS, BASED ON WORLD BANK DATA

EC4: Industry relocation

Definition: *Location choice of (heavy) industries that already depend, or will depend on hydrogen as a feedstock or energy source.*

A number of factors determine industry's location choices. Given existing (investments in) assets, infrastructure, and supply chains, not all industries have an 'option' to relocate without incurring substantial costs. An important factor, particularly in energy-intensive industries where energy and feedstocks form a major share of the costs, industries may seek to co-locate close to sources of cheap and abundantly available energy. Industry in north-west Europe has traditionally benefited from cheap supplies of local or imported natural gas to meet energy needs and for domestic hydrogen production. However, with the 2022 energy crisis, gas prices have skyrocketed and are unlikely to return to their pre-2022 levels in the near future.[52] Therefore, industry in north-west Europe and other import-dependent regions may consider relocating to low-cost energy and hydrogen production areas, such as the Persian Gulf, Latin America, North Africa and Australia.

52 Fulwood, M., September, 2022. *Europe's Infrastructure and Supply Crisis*. The Oxford Institute for Energy Studies. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/09/Europes-Infrastructure-and-Supply-Crisis.pdf.

The reverse is also possible. For example, chemical industries may choose to remain around knowledge or demand centres. This is especially logical for fine chemicals or organic bulk chemicals, the part of the chain which follows the energy-intensive petrochemical processing. This means that hydrogen value chains may follow the industry, rather than the other way around. There are only a few places where return on investment will be favourable. Location choices are therefore influential, and will play out in any decision to develop hydrogen production and hydrogen consumption for 'green' chemistry. Industry location choices have more determinants, such as access to infrastructure, proximity to demand markets and transportation costs. The location selection process and its outcome will influence how low-carbon hydrogen value chains emerge and expand, particularly for the Rotterdam cluster, which hosts heavy industry and supplies the ARRRA region.

ENVIRONMENTAL FORCES

ENV1: Climate change-induced extreme weather event

Definition: *Physical and socio-political impact of climate change-induced extreme weather events in north-west Europe and other key geographic nodes in the emerging low-carbon hydrogen value chains.*

The unpredictable impacts of climate change may affect asset and value chain developments, in two primary ways: physically and socio-politically. These may increase project development risks. Examples of physical impacts include: more frequent and more severe weather events, in north-west Europe and in other geographical areas key to low-carbon hydrogen value chains, such as coastal production facilities and transport nodes, rising seawater levels, destructive storms, frequent floods, heavy rainfall, extreme droughts. The social, economic and political effects will impact the stability of countries and value chains.

Climate change and its geographically specific manifestation is becoming increasingly clear, but the longer term impacts are not.[53] Therefore, alongside physical effects, the risk perception of climate change will influence socio-political discourse and decision-making. With rapid changes in weather events, and their consequences, risk perceptions could change suddenly and dramatically. What remains uncertain, however, is how disruptive climate events will be for industrialised economies, particularly when considering the volatility of hydrogen and its derivatives and the associated safety risks. Some notable recent examples of severe weather events to illustrate such impact:

53 Intergovernmental Panel on Climate Change, 2021. *Sixth Assessment Report*. https://www.ipcc.ch/report/ar6/wg2/.

- Droughts in Europe and China in the summer of 2022 broke numerous records, with Europe's being the worst in 500 years.[54] Droughts reduced agricultural output and hydropower generation, disrupted water cargo transport due to low water levels in rivers and nuclear and thermal power generation due to higher water temperature in rivers. Transport was also disrupted as the excessive heat caused material railways and bridges to expand.
- Windstorms that passed Europe in the winter of 2022 caused over €3.8 billion in damage and storm gates had to be closed frequently, thus interrupting maritime trade.[55]
- A blizzard that engulfed Texas in February 2021, not only took out the state's energy grid, but also paused oil and gas extraction as well as refining in the Gulf of Mexico.[56]

ENV2: Scarcity of raw materials

Definition: *Scarcity of raw materials for energy, energy technology, infrastructure and consumer goods.*

The energy transition requires a tremendous scale-up of renewable energy technologies, many of which require scarce metals or materials. For example, Polymer electrolyte membrane (PEM) electrolysers rely heavily on platinum and iridium as catalysers of the electrolysis process. Resource scarcity for key transition materials is a given, especially considering the long lead times for mining project development. Scarcity of these materials will pose considerable constraints on technology upscaling and roll out. The extent to which this will be a threat to decarbonisation depends on how this scarcity is handled. However, the scarcity could be offset by a faster move towards a circular economy with the reuse of critical materials, or by diversifying supplies and increasing prices for rare materials, which will drive innovation and encourage other materials to be used for hydrogen production systems.[57]

54 BBC, 17 September, 2022. *China, Europe, US drought: Is 2022 the driest year recorded*? https://www.bbc.com/news/62751110.

55 AON, April, 2022. *Q1 Global Catastrophe Recap*. https://www.aon.com/reinsurance/getmedia/af1248d6-9332-4878-8c92-572c1bf3c19d/20221204-q1-2022-catastrophe-recap.pdf.

56 The University of Texas at Austin Energy Institute, July, 2021. *The Timeline and Events of the February 2021 Texas Electric Grid Blackouts*. https://energy.utexas.edu/research/ercot-blackout-2021.

57 European Commission, 2 September, 2020. *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*. https://ec.europa.eu/docsroom/documents/42849.

Competition regarding access to resources may induce local conflicts and political instability, local exploitation and human rights abuses around production locations. It may also lead to new dependencies, as the processing of raw materials will also be unevenly distributed around the world, with key processes for metals concentrated in China and Indonesia.[58] This, in turn, could lead to increased protectionist policies and shifts in geopolitical balances between states. Scarcity could also lead to developing new sources or a reorientation towards less efficient but more secure supply chains, thus driving up the price of hydrogen.

ENV3: Land and water availability

Definition: *Availability of land to produce renewable energy locally and to build hydrogen infrastructure, and availability of water for electrolysis to produce green hydrogen.*

The availability of land and water is a prerequisite to produce hydrogen locally and essential for future hydrogen exporters. Land is needed for infrastructure and hydrogen production, both for electrolysers, as well as energy feedstocks, such as solar PV and wind energy. Fresh water is needed for electrolysis. If sea water has to be used as a substitute for scarce fresh water, this will have to be desalinated, again requiring land.

Land scarcity and unwillingness to alter existing land use in north-west Europe, particularly in the Netherlands, must be included in the discussion on where hydrogen value chains should be developed.[59] North Africa, for example, not only offers advantages in the cost of renewable energy, but has more accessible land relative to north-west Europe. This plays a role, since low costs of production do not necessarily offset the efficiency losses from conversion and long-distance transport of hydrogen.

Different functions may be competing for the same water and land resources, such as nature, energy, agriculture, industry or even military use, as is currently the case in the North Sea.[60] These functions often interact with each other, positively and negatively. For example, desalination of water in dry coastal regions could reduce the unit cost of desalination and therefore reduce the cost of drinking water. Similarly, production of green ammonia could reduce the local cost of fertiliser production and stimulate local agriculture, thus creating a virtuous cycle for

58 Castillo, R., Purdy, C., July, 2022. *China's Role in Supplying Critical Minerals for the Global Energy Transition*. Brookings Institution. https://www.brookings.edu/wp-content/uploads/2022/08/LTRC_ChinaSupplyChain.pdf.

59 Notermans et al., *Hydrogen for the Port of Rotterdam in an International Context - a Plea for Leadership*, p.13

60 Government of The Netherlands, n.d. *Noordzeeloket*. https://www.noordzeeloket.nl/en/functions-and-use/.

economic development. On the other hand, hydrogen infrastructure and electricity generation for hydrogen production in areas such as the North Sea may displace other activities or uses.

ENV4: Sustainability pathways

> **Definition**: *Political choices of how and how quickly to decarbonise national economies, on a scale between a pragmatic and idealistic energy transition.*

While there is general consensus on the need to address climate change and many countries and organisations have adopted the Paris Agreement, there is still the choice of which decarbonisation route to pursue. This includes the extent of climate mitigation as well as adaptation policies. With respect to hydrogen, there are different regional pathways currently chosen. The EU, for example, is aiming for a 'deep' green transition, with hydrogen produced increasingly quickly from renewable electricity. Others, such as the Middle East, US, Japan and South Korea are more 'colourful' and pragmatic in their choices for alternative energy sources, and the timelines they will follow.[61] So, it is not only a question of 'how deep', but also, 'how deep, where, when initiated, how fast, and does it reach the targets set in the Paris Agreement?'

The choice for a certain pathway is often value-driven, with a combination of science, ideology, vested interests and emotion. The choice involves discussing what is right in the philosophical sense, as well as what values and worldviews drive the decision-making. The topic is politicised and impact is bi-directional: scientific solutions are sometimes discounted from an environmental perspective, which can shift support for hydrogen. 'Pragmatic' considerations are also value-driven or interest-driven. In the pragmatic sense, the desirability of solutions is highly dependent on their expected success in decreasing CO_2 emissions. If adopting blue hydrogen allows this, it is the preferred solution. In other words, there is still value and emotion in such a CO_2 reduction pathway, but there is also concern about this being successful.

The difference with the idealistic pathway is that the value of a measure depends on its intrinsic value. That is, some measures are 'good' because they are principally clean and disrupt fossil fuel systems, while other measures are 'bad' because they principally support continued fossil fuel use. This can determine how quickly decarbonisation is feasible, but it can also determine certain hydrogen development

61 *Colourful* refers to the various colours associated with methods for producing hydrogen, such as grey hydrogen from hydrocarbons, green hydrogen from electrolysis based on renewable electricity or pink hydrogen from nuclear power.

options. For example, sustainability 'pragmatism' is seen as a core rationale for investing in blue and pink hydrogen. This should quickly reduce emissions while providing opportunities to scale-up production, thus allowing demand to emerge. At the same time, it buys time for industry to restructure in line with its investment cycles. On the other hand, since technologies such as carbon capture, utilisation or storage (CCUS) have not yet been proven at scale, pathways such as blue hydrogen may be considered dogmatic.[62]

POLITICAL FORCES

P1: Leadership in hydrogen and hydrogen technology development

> **Definition**: *The extent of north-west European governments' leadership to shape hydrogen technology and hydrogen market development. This includes support for developing hydrogen technologies and forming hydrogen market, as well as balancing supply and demand.*

The role of government support, intervention and public infrastructure is based on the idea that a government can, and sometimes should, help to create business opportunities on the demand and supply sides of the market, or even make parts of the market public. This de-risks market entry and facilitates large-scale projects designed to achieve economies of scale for private actors, while ensuring competitiveness with foreign (state-owned) companies. Government support is necessary to overcome key societal challenges in the energy transition, and more specifically to support new technologies and infrastructure, and to fund research and translate this into applications.[63]

If a government does not or is not willing to 'kick-start' the hydrogen industry, it risks disincentivising private companies from pursuing low-carbon hydrogen as it remains uncompetitive in terms of costs. This will block progress of hydrogen adoption within the EU, while enabling countries with state-owned enterprises and national ambitions, such as Japan, to achieve market leadership and secure access to promising green/blue hydrogen locations, for example in the Middle East and North Africa, Chile and Australia. State leadership, however, also has its risks. Governments mis-reading market developments may offer incorrect incentives and hamper further market development. An example of this is the EU's over-emphasis on the gaseous forms of hydrogen, neglecting the importance of liquid forms as import carriers.[64]

62 Interview with senior energy expert, October 2022.

63 Mazzucato, M., 2016. *From market fixing to market-creating: a new framework for innovation policy*. Industry and Innovation, 23(2), pp. 140-156.

64 Clingendael International Energy Programme, 2022. *Managing Future Security of Low Carbon Hydrogen Supply*, p. 12.

P2: Degree of global cohesion

Definition: *The degree of international cohesion and collaboration, or extent of fragmentation between countries and different political-economic blocs of countries.*

In a globally cohesive and integrated world, states work together under a set of clearly established rules. Within a cooperative regime, some states play a more important role in governing the systems and accruing the benefits of doing so, while others follow. The costs and benefits generated by the system are not evenly shared across states and thus, can be a source of instability and conflict. These conflicts, however, are regulated and even de-escalated. In a cohesive world, disputes between states, or non-state actors and states can be settled through international or multilateral mechanisms, such as the World Trade Organisation (WTO). Nevertheless, the rules of the regime may change, as well as the position and power of states in the system. In recent years, institutions led or influenced by the West have come under pressure, often from Western states themselves. For example: the US has previously blocked the WTO Appellate Body, its dispute settlement mechanism, from operating effectively, seeing its rulings as a risk to US interests.[65] Russia and China, meanwhile, are more actively using their veto powers at the UN Security Council, while China did not recognise the ruling of the International Court of Justice in favour of the Philippines over the South China Sea dispute.[66]

In an incohesive and disintegrated world, there are no longer any clear, agreed-upon mechanisms that regulate the interactions between states. Power play and individual state interests become more important. A 'realist' mindset prevails – a situation with stark hierarchies and zero-sum calculations in an anarchic global system. Conflicts are less easily defused. In response to global disintegration and the re-emergence of nationalism, states can form strategic alliances or small 'blocs' as a way of adding force and counter-balancing stronger states. This results in fragmentation.

A re-emergence of competing empires following a perceived unipolar world order could make it difficult to establish international norms and standards for the developing hydrogen markets, resulting in less globalised trade in hydrogen and this could encourage differentiation in hydrogen technologies. This means that within

65 Erken, H., 10 December, 2019. *The WTO dispute settlement crisis. Back to the GATT regime*? RaboResearch - Economic Research, Rabobank. https://economics.rabobank.com/publications/2019/december/the-wto-dispute-settlement-crisis/.

66 The Economist, 18 June, 2020. *The UN's structures built in 1945 are not fit for 2020, let alone beyond it*. https://www.economist.com/special-report/2020/06/18/the-uns-structures-built-in-1945-are-not-fit-for-2020-let-alone-beyond-it; Phillips, T., Holmes, O., Bowcott, O., 12 July, 2016. *Beijing rejects tribunal's ruling in South China Sea Case.* The Guardian. https://www.theguardian.com/world/2016/jul/12/philippines-wins-south-china-sea-case-against-china.

political-economic blocs hydrogen trade could be developed, but trade between those blocs would be hampered. Competition between trade blocs can both stimulate and hamper hydrogen developments within the bloc. It can be spurred on as each bloc seeks to foster its own technology and industry, and allow this to develop under societal and political pressure from within. But this approach will also be hampered by limited exchange of new inventions and may induce increased costs.

P3: Rules setters in global markets

Definition: *Acquisition and use of rule and norm setting power, partly by capitalising on early mover advantages, and setting the pace and standards for global hydrogen value chains.*

To a certain extent, rule setting is manifested by the influence existing institutions and players as well as market and technology rules exercise on how global trade functions. This can be viewed as a dichotomy between the developed and emerging hydrogen markets in the West (the US, UK, EU, Japan and South Korea) and the East (China). This also includes the geographic 'middle' (Russia, India, Turkey, Saudi Arabia, UAE and Qatar). If Western rule setters remain in the lead, we can expect continuing competitive and open global trade, regulated by institutions such as the WTO. Large Western multinational companies, who have had a lead in rule setting in the oil and gas sectors, will also be instrumental in setting the rules and norms for the hydrogen market.

Eastern rule setters may:

- install new institutions;
- push existing national or regional institutions (the Asian Infrastructure Investment Bank or the Eurasian Economic Union) to the global level;
- promote market mechanisms that do not function based on open competition, including Western organisations.

The hydrogen market may also be shaped by largely non-Western companies and state-owned enterprises that pursue their government's national priorities abroad. Early movers in the hydrogen value chains will be able to set the international rules and norms for how the hydrogen value chain will function and how hydrogen could be traded. For example, consider Japan's role in forming liquid natural gas (LNG) markets. Rule setters may weaponise the hydrogen market by gate-keeping certification and the trading mechanisms, even if hydrogen production becomes less concentrated than fossil extraction.

P4: Energy security in north-west Europe

Definition: *The uninterrupted availability of energy sources at an affordable price in north-west Europe, including energy infrastructure resilience.*[67]

This force refers specifically to the physical operationalisation of energy security, as shaped by exogenous (geopolitical) developments, rather than energy security as a policy target. After years of being a secondary concern, energy security has now become a central issue in north-west Europe. This is due to political (in)stability in exporting and hub countries, and states exercising their control over supply, technology, facilities and infrastructure, as well as using key transport routes to exert political pressure. North-west Europe is particularly sensitive to fluctuation in energy security as it is, and will most likely remain, an import-dependent region. Prioritisation of energy security changes the logic of value chain development, as assets are no longer primarily built to optimise for efficiency.

The future diversification of hydrogen supply is often perceived as a means to enhance energy security by spreading the risks of potential chain disruptions and by choosing to deal only with stable and politically friendly regimes. However, in extreme forms, cartel dynamics similar to OPEC, among like-minded exporting countries, may influence market outcomes, thus affecting the consistency of supplies in an emerging market where few alternative suppliers are present. Diversification also improves the resilience of the technical system to provide an uninterrupted supply of energy. Even with a large number of suppliers, energy production may be concentrated in a small number of locations. It may also become dependent on scarce bottleneck infrastructure facilities, due to the high costs of constructing additional and alternative capacity.

TECHNOLOGICAL FORCES

T1: Learning curve for non-hydrogen electricity storage

Definition: *Learning rates for electricity storage technologies to substitute hydrogen.*

One of the main reasons to adopt hydrogen in a future energy system is its complementary functionality to electricity. Hydrogen is a gaseous energy carrier that can be stored and transported more easily than electricity over long distances. Rapid development of non-hydrogen electricity storage, such as battery technology or mechanical energy storage, could serve as a substitute for one of the main uses of

67 International Energy Agency, n.d. *Energy security*. https://www.iea.org/topics/energy-security.

hydrogen and render it less viable. The extent to which hydrogen will still be required will depend on the extent to and the scale at which electricity storage and discharge can be flexibly applied in different time scales of hour-by-hour balancing, as well as days, weeks and months. This will also shape the role of hydrogen in the rest of the energy system. However, even with rapid learning curves for non-hydrogen storage technologies, it will probably take decades to reach maturity and large-scale adoption levels. The unpredictability of these timelines increases the capex risk for hydrogen projects, as they may be rendered obsolete by competing technologies during their lifecycle. An example of such a timeline is the rapid increase in heavy duty electric vehicle use. These vehicles are becoming increasingly competitive, not only compared to hydrogen vehicles, but also to existing internal combustion engine options.[68]

T2: Access to key hydrogen technologies

Definition*: Access to affordable and mature hydrogen technologies in north-west Europe.*

The innovation progress for key hydrogen technologies such as electrolysers, fuel cells, hydrogen-adjusted gas turbines including conversion and storage technologies is still ongoing. Feasible cost-effective improvements and technology scale-ups are critical for forming hydrogen value chains. However, the availability of technology is not only determined by innovation. It depends on a variety of other factors such as resource scarcity, policies, and the extent of globalisation. if demand centres and technology winners are dominant outside Europe, north-west Europe may have limited access to electrolyser technology.

Technology development and access risks are numerous. For example, if anticipated efficiency gains are not achieved or no alternatives for scarce materials found, innovation in electrolysis technology could fail. Hydrogen may not be positioned as competitive in the appropriate time frame. It will not be sufficient to achieve efficiency gains over competing technologies: early deployment and scale-ups will create lock-in effects, as is already occurring with passenger electric vehicles.

68 Rathi, A., 7 June, 2022. *The Future of Carbon-Free Trucking Isn't Batteries… Yet*. Bloomberg. https://www.bloomberg.com/news/articles/2022-06-07/the-future-of-trucking-isn-t-batteries-yet-says-volvo.

T3: Emergence of intercontinental supergrids

Definition: *The realisation of large-scale, intercontinental and transcontinental, electricity grids that substitute hydrogen as an energy carrier.*

In a world free of security and geopolitical risks, pipelines and power lines are often the preferred option to move large quantities of energy, even over long distances. This is an energy-efficient and cost-effective transport mode, especially if the (primary) energy source is a gas. However, with the destruction of Nord Stream 1 and 2, and the consequences of the Russian-Ukrainian war, future vulnerability and lock-in to billion euro pipeline and powerline projects could be mitigated by favouring hydrogen (carrier) transport by ship.

On the other hand, a more united Europe may opt to move vast quantities of hydrogen, electricity to make hydrogen, or simply electricity as the final energy carrier through a grid within the EU, or, for example, between the EU and North Africa. This is already the case with projects being considered and realised under the umbrella of the European Super Grid.[69] Long-distance electricity transmission is increasingly considered technically and economically viable, such as moving energy from the central US to the coasts, from northern to southern Germany, or across China.

Such grids already exist for natural gas. Electricity is also transported, although with limited international interconnector capacity. In the aftermath of the February 2022 invasion, Ukraine was able to switch from synchronisation with the Commonwealth of Independent States (CIS) grid to the European continental grid within a month, and the Baltic states claim they can make this switch within 24-hours if Russia cuts power supply.[70] Moreover, a supergrid does not necessitate only one investment decision; it can grow out of many smaller investment decisions for bilateral projects or even single lines and interconnectors. Such emergence is of particular interest to the Port of Rotterdam. It determines whether energy can arrive by ship or pipeline/powerline, and to what extent Rotterdam is strategically positioned at the beginning of inland transport into north-west Europe. This is certainly the case for Nordic and UK energy from the North Sea, but the question is whether Rotterdam could play such a role for energy generated in the Mediterranean, for which transport lines may end, and not start, in Rotterdam.

69 Rucci, T., 27 January, 2022. *The European Super Grid: A solution to the EU's Energy Problems*. Eyes on Europe. https://www.eyes-on-europe.eu/the-european-super-grid-a-solution-to-the-eus-energy-problems/.

70 Sytas, A., 13 July, 2022. *Baltics would switch to European grid in a day if Russia cuts power - Lithuania*. Reuters. https://www.reuters.com/business/energy/litgrid-says-baltics-can-connect-european-grid-within-24h-if-russia-cuts-power-2022-07-13/.

The extent to which the European Hydrogen Backbone (EHB) will be realised will shape opportunities for intra-regional hydrogen trade and import opportunities from the rest of Europe. There are still technical and political barriers to realising an electricity supergrid, but, if realised, supergrid emergence outside the US could upset hydrogen value chain dynamics. This would be particularly impactful if electricity grids are further connected between Europe and North Africa.

T4: Emergence of high-energy digital applications

Definition: *A new technology or functionality that causes an extreme peak in electricity consumption enters the market with high adoption rates.*

The emergence of (more) high-energy digital applications could encourage electricity demand, causing peaks and/or higher constant usage. If energy prices return to pre-February 2022 levels, this could once again stimulate an increase in energy consumption, thus putting even more pressure on the energy system. An example of this is cryptocurrencies, the 'mining' of which skyrocketed electricity use in recent years, often catching governments off guard. Bitcoin, the largest of the world's 19,000+ cryptocurrencies, annually consumes as much electricity as Argentina's population of 45 million people.[71] Bitcoin mining was concentrated in China, until its government's crackdown in 2021, with mining currently concentrated in low-cost but high-emission Kazakhstan and the US.

This is an example of an unexpected, large-scale digital energy consumer. Future consumers could extend to artificial intelligence (AI) or yet to be identified high-energy digital applications. Meta itself has recently raised concerns over AI's increasing energy use and environmental footprint.[72] This may increase the demand for hydrogen in the EU, even if hydrogen is not used directly for digital applications, the higher scarcity of directly generated green electricity may push applications such as transport towards hydrogen, instead of battery EVs. Hydrogen can also serve as a buffer in the energy system, which will help balance the grid to meet demand fluctuations.[73]

71 Hinsdale, J., 4 May, 2022. *Cryptocurrency's Dirty Secret: Energy Consumption*. Columbia Climate School. https://news.climate.columbia.edu/2022/05/04/cryptocurrency-energy/.

72 Wu, C., et al, 9 January, 2022. *Sustainable AI: Environmental Implications, Challenges and Opportunities*. https://arxiv.org/pdf/2111.00364.pdf.

73 However, hydrogen itself can be seen as a high-energy (non-digital) energy application, as it requires large quantities of renewable electricity for electrolysis, which remains inefficient in terms of the amount of energy retained in the process. This could challenge the use of hydrogen in the system when competing with other electricity uses. On the other hand, if the EU/north-west Europe need to import large amounts of energy and can only do this by importing hydrogen, an added benefit of these imports is that they can be placed into buffer storage with a more limited energy penalty.

5 CREATING SCENARIOS FROM FORCES

In the previous chapter, the 20 most important SEEPT forces were identified. The next step in the eight-step scenario planning process outlined in Figure 1, is to identify the key critical uncertainties to shape the scenarios. The forces were compared based on:

1. the most impact of a force on other forces;
2. the impact of forces on the focal issue;
3. the highest likelihood of the force occurring.

SELECTING THE CRITICAL UNCERTAINTIES FROM THE SEEPT FORCES

The first comparison is achieved through Cross-Impact Analysis (CA), while the latter two are achieved through the Wilson Matrix (WM). The WM divides forces into predetermined trends, secondary forces and critical uncertainties, and normally serves as the basis for selecting scenario frameworks. The research team opted to use both the WM and CA to select the critical uncertainties, combining the WM's median selection and prioritising the CA outliers by ranking preferences. This enabled generally agreed-upon and challenged forces to be included, and which has therefore created a more diverse scenario framework. The results of the CA and WM are presented below in Table 3 and Table 4, respectively.

Rank	Force that has the most impact on other forces in the list	
1	ENV4:	Sustainability pathways
2	S1:	Social structure
3	P3:	Rule setters in global markets
4	ENV1:	Climate change-induced extreme weather events
5	EC1:	CO_2 abatement policies

TABLE 3. RESULTS OF THE CROSS-IMPACT ANALYSIS

Wilson Matrix		Potential impact		
		Low	Medium	High
Probability	High		ENV1: Climate change-induced extreme weather events ENV4: Sustainability pathways EC: CO_2 abatement policies ENV2: Scarcity of raw materials ENV3: Land and water availability	T2: Access to key hydrogen technologies P4: e energy security P3: Rules setters in global markets P1: Leadership in hydrogen and hydrogen technology development
	Medium		S1: Social structure S3: Energy (distribution) justice EC2: Stability of global financial markets P2: Degree of global cohesion S4: Availability of human capital EC3: Extent of globalisation	S2: Public acceptance of the energy transition T1: Learning curve for non-hydrogen electricity storage EC4: Industry relocation
	Low	T4: Emergence of high-energy digital applications	T3: Emergence of intercontinental energy grids	

TABLE 4. RESULTS OF THE WILSON MATRIX

The research team's use of the WM and CA resulted in the following critical geopolitical uncertainties that will shape the emergence of low-carbon hydrogen value chains:

- P4: Energy security
- S1: Social structure
- ENV4: Sustainability pathways
- P1: Leadership in hydrogen and hydrogen technology development
- T2: Access to key hydrogen technologies
- P3: Rule setters in global markets

CONSTRUCTING SCENARIO FRAMEWORKS

The six forces selected as critical uncertainties in the previous step serve as the foundation of the four scenarios. While all the forces are taken into consideration when developing the scenario narratives, it is the extremities of the critical uncertainties that formulate the bounds of the scenario matrix. These options are presented in Table 5 below.

Variation	P4: Energy security	S1: Social structure	ENV4: Sustainability pathways	P1: Leadership in hydrogen (technology) development	T2: Access to key hydrogen technologies	P3: Rule setters in global markets
Extremity A	Increased energy security in north-west Europe	Individualistic society	Idealistic pathways	State-led development	Abundant access	West sets the rules
Extremity B	Decreased energy security in north-west Europe	Collective society	Pragmatic pathways	Market-led development	Scarce access	East sets the rules

TABLE 5. VARIATIONS OF THE SIX CRITICAL UNCERTAINTIES THAT ESTABLISH THE BOUNDS OF THE SCENARIOS

Even with the key forces reduced to six, each with two variations, this generates a large number of possible combinations. At this stage, a morphological analysis was performed to construct coherent foundations based on the various combinations of the force variations. There is no predetermined approach to establish the scenario frameworks. It is an art rather than a science, and it is not designed to create four deterministic worlds. Instead, it is designed to present extremities and intuitively craft the possibilities within them, along which geopolitical and societal dynamics can evolve.

The morphological analysis is conducted qualitatively, balancing the internal consistency of a scenario in combination with its force variations, as well as scenario differentiation in the overall combination of forces. Using two variations of six forces can create many possible combinations. Therefore, the emphasis is placed on the storytelling aspect, rather than the 'correctness' of a particular combination. The process aims to create two 'extreme' scenarios, that serve as the outer bounds of the plausible worlds, while the other two present alternative, viable outcomes within those bounds. The following combinations were produced as a result:

Scenario	P4: Energy security	S1: Social structure	ENV4: Sustainability pathways	P1: Leadership in hydrogen (technology) development	T2: Access to key hydrogen technologies	P3: Rule setters in global markets
Revival of the Rhineland Model	Increased	Individualistic	Pragmatic	Passive	Abundant	West
The Right of Sun Tzu	Decreased	Individualistic	Pragmatic	Passive	Scarce	East
Europe's Eureka	Increased	Collective	Idealistic	Active	Abundant	West
Broken Bridges	Decreased	Collective	Idealistic	Active	Scarce	East

TABLE 6. MORPHOLOGICAL ANALYSIS OF THE CRITICAL UNCERTAINTIES

6 THE SCENARIOS

The four scenarios summarised below and detailed in the following pages, represent how geopolitical dynamics and societal changes may evolve between now and 2040, and how these may impact the emergence of low-carbon hydrogen supply and trade networks in the ARRRA supercluster.

The scenario illustration below captures a set of continuums, rather than discrete outcomes in the four corners. The prevalence of one scenario does not mean elements of other scenarios cannot feature; the movement towards one scenario 'extreme' can be rapidly reversed with a wildcard 'what if' event, and thus project an alternative scenario to the forefront.

The scenarios are created based on a number of building blocks. At the core of the scenarios are the *critical uncertainties*: geopolitical forces which have a high likelihood of occurring and a high impact on developing hydrogen value chains in the ARRRA region. This may be through direct impact, or second order effects from interlinkage with other, more closely related forces. They also reflect *predetermined trends*, and *secondary forces* that bear relevance, but without a high impact. Implications of the scenarios for hydrogen trade and supply network development are described in the following chapter.

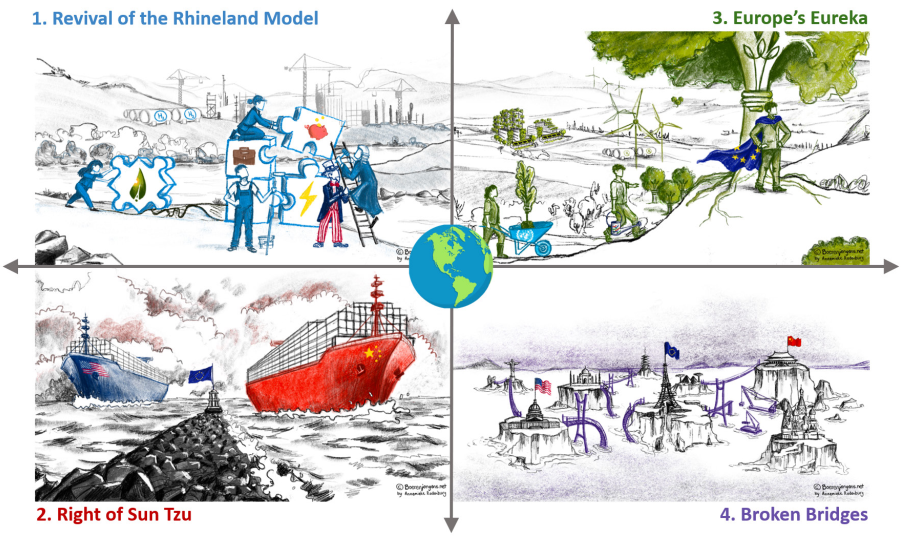


FIGURE 4. SCENARIO MATRIX WITH THE FOUR SCENARIOS

SCENARIO 1: REVIVAL OF THE RHINELAND MODEL

Looking back, the 2020s were a tumultuous decade in global history. Russia's invasion of Ukraine marked the end of an era. The US, with support from the UK and eastern Europe, showed strong resolve in countering Russia's military onslaught. Germany, France and Italy, at the helm of the EU response, took a more cautious attitude. Much of the rest of the world looked on as events unfolded. When the dust settled, EU-Russia relations stabilised after sanctions were levied, but loosely enforced. Commodity markets used this opportunity to service severed relationships. Russian oil and oil products continued to find consumers, and small volumes of Russian gas found its way into the internal EU market through spot volumes and third-country transit pipelines, with Turkey in particular finding itself in an advantageous position as a new energy hub.

Global trust in institutions waned in the response to the COVID-19 pandemic and the energy crisis. The US remained the global rules and norms setter, as well as the main security provider to Europe. The energy crisis precipitated by Europe's response to Russia's war reverberated through north-west European economies. At the same time, China entered its version of Japan's 'Lost Decade', as domestic growth stagnated after the collapse of the real estate asset bubble. Together with US interest rate hikes, Chinese and European demand slumps reversed the commodities market rally. The wave of high prices for food, energy and consumer goods left scars on the politically splintered and economically strained societies of north-west Europe.

At first, European governments 'turned inward' as they struggled to provide affordable energy, sustainable infrastructure, proper housing, accessible healthcare, and inclusive education. Most resorted to short-term fixes rather than long-term solutions, as they lacked political will and struggled with the depletion of government treasuries and high public debt. In the absence of strong leadership, the EU's push for the energy transition dwindled.

Initially, Western societies looked to populist leaders to solve the problems that 'the middle' had been unable to fix for years. Political elites were under sustained pressure from the likes of the *Boerenprotest* in the Netherlands, *Gillets Jaunes* in France and the remnants of the anti-COVID-19 measures movement in Germany. However, the 2030s brought a brighter outlook. After several election cycles, it became clear that the prominent populist parties were unable to fulfil their promises, and citizens became increasingly disenfranchised and withdrawn from politics. The era of polarisation eventually catalysed a twist – a return of the centre.

Protagonist	After years of strikes by farmers, teachers, public transit workers and healthcare staff, and protests from aggrieved and marginalised social groups, a majority coalition government led by the Christian Democratic Alliance (CDA) settled into office in the Netherlands. CDA's charismatic leader, toughened by years as a negotiator between the government, business and workers, formed the new government based on tri-party concessions. Business elites recognised that social discontent driven by income and wealth inequality was no longer sustainable, and that it was time to accept changes. Similar leadership changes in Belgium and Germany pushed for changes at EU level.

So by 2030, north-west European centrist politicians had learned their lesson: neoliberalism had no solution for the unsustainable rates of inequality that drove public discontent. Instead, they once again promoted a social market economy, akin to the post-World War II and pre-Washington Consensus period in Europe. While the US continued to be the global norm and rule setter, north-west Europe was fairly free to reorient its economic ordering. Under the so-called *Rhineland Model*, political rhetoric in north-west Europe focused on wages, redistributing wealth, and a universal basic income. Furthermore, fiscal policies were oriented to social welfare through higher corporate and windfall taxes. At the same time, politicians sought collaboration with the private sector and (environmental) not-for-profit organisations to find solutions to pressing collective issues, such as the energy transition. Companies accepted lower short-term returns in exchange for long-term strategic advantages.

Similar to the growth of oil trade and petrochemicals in the 1950s and 1960s, corporatist leadership aligned states with industry to secure a pragmatic transition pathway. EU member states promised the private sector regulatory continuity, while embracing protectionist measures under the aegis of EU-wide security of supply and strategic autonomy. Credible companies, with energy system knowledge and sufficient capital for large investments, committed to upholding stakeholder interests in a symbiotic relationship with the EU and national governments. Industrial policy dominated the European innovation agenda, and with only moderate government co-financing for sustainability, companies focused on low-risk, incremental innovation for key energy transition technologies. The majority of energy demand had become electrified, and alternative energy sources were only sought for hard-to-electrify demand.

Resurgent state involvement can drastically reshape a market. In the 1950s, Iran, Iraq and Venezuela, among others, sought to nationalise their oil production. They extended their challenge to international oil companies (IOCs) such as Shell and BP when Iran, Iraq, Kuwait, Saudi Arabia and Venezuela founded the Organization of the Petroleum Exporting Countries (OPEC) in 1960. OPEC was intended to stabilise oil supply and income from it, realign the market to the planning cycles of the national oil companies (NOC), and raise the members' influence over market prices. With increased command of the market, the NOCs bought or forced out the IOCs to control their own oil reserves and assets.	**Historical Analogy**

Increasingly climate-concerned European societies sought to punish heavy polluters – oil and gas companies in particular – but it became clear that the transition could not happen without them. The heavy polluters repositioned, funding investment in renewables and hydrogen from capital accumulated from high oil and gas prices. As 'silent minority partners' to the 'new majors' – a handful of previously rebranded fossil giants, emerged as renewable energy companies and upscaled energy cooperatives. Social groups, particularly those co-located with large industries, feared unfair treatment and distribution of land, water and electricity in favour of industry. Promises by industry to share the burden of funding the energy transition did little to taper distributional justice concerns, while stakeholder-led companies emerged as trust leaders.

The EU maintained pragmatic relations with the US, Russia and China, though dependency on Russian fossils had been partly substituted with liquid natural gas (LNG) flows from the United States, Australia, Algeria and Qatar, and increased crude oil and oil-based flows from the Middle East. Further east, domestic growth slowdown and skyrocketing youth unemployment restrained China, which remained reluctantly cooperative with the US-led economic order. Globally, structural underinvestment in fossil extraction solidified a comparative advantage for wind and solar power, and associated hydrogen production. Japan and South Korea sought hydrogen to diversify their energy mix, establishing themselves as both technology and demand centre leaders. Saudi Arabia, UAE and Australia led the way in the export of green ammonia and methanol.

Early indicator pointing to the world heading towards this scenario	EU and member states have increased government intervention in the private market to stabilise the energy cost fallout from the war in Ukraine on the European population. The measures have included bailouts and nationalisation, such as the case of Germany's Uniper, EU-wide windfall taxes on energy companies, and EU-wide joint purchasing of natural gas and other solidarity measures that introduce rules for the functioning of energy markets.

In north-west Europe, investment in offshore wind required expansion and reinforcement of electricity grids and conversion to other energy carriers, in particular, molecules such as hydrogen to absorb power into the system. This, together with security of supply policies to mitigate dependencies, stimulated regional hydrogen development, but imports from outside the EU remained modest. The Port of Rotterdam became a regional hub for ammonia and methanol imports, which, in combination with locally produced blue and green hydrogen, further reduced the Port of Rotterdam's share of fossil fuel throughput.

LNG retained significance, particularly as feedstock for blue hydrogen, complemented by newly constructed modular nuclear facilities in the port which powered newly electrified facilities. The Port of Rotterdam successfully scaled a circular economy business model with pyrolysis oil processing. The port's bunker market was increasingly serviced via methanol. There was a moderate increase in storage terminal demand, as hydrogen density requirements offset decreases in fossil fuel throughput. During the 2030s, industry majors developed vertically-integrated value chains that serviced the ARRRA region, with local hydrogen value chain links requiring Dutch public co-ownership to prevent hostile takeovers from Chinese, US and Middle Eastern companies, state-owned funds and financiers.

SCENARIO 2: THE RIGHT OF SUN TZU

In the late 2020s, the relationship between the US and its two main Gulf allies – Saudi Arabia and the UAE – faltered. The Joint Comprehensive Plan of Action, Iran's nuclear deal – and the US' conflicted position within it – failed to restrain Iran's ambitions. Saudi Arabia perceived the US' attempts to reduce its security commitments to the region, by brokering the normalisation of relations between Israel and UAE, as an inadequate response to an increasingly bold Iran. Strengthened trade ties between the Arab countries and Russia in the wake of the Ukraine war proved to be the final blow to the US-Gulf relationship. The US withdrew its security guarantees to its Gulf partners which triggered them to break their fossil and emerging blue hydrogen exports to the West. As the Gulf reoriented to the premium markets of East Asia, China, now the Gulf's largest trading partner, promised the necessary military means and guarantees to foster stability in the region.

Early indicator pointing to the world heading towards this scenario	The US decoupling from China in the global system is nowhere more evident than in the strategic semiconductor sector. In 2022, within a short period, the US issued a broad set of prohibitions on export of high-end semiconductors to China and passed the CHIPS and Science Act to reshore the microchips industry back to the US. The prohibition includes not only US exports, but exports of non-US companies that use US technology, therefore covering all leading semiconductor manufacturers. This early indicator shows how the global system can be divided step-by-step, one critical industry at a time.

Changes in the geopolitical balance in the Middle East reinforced a period of global bipolarism between East and West, where China increasingly took the lead. American spending on national defence doubled to 8% of GDP, accelerating its arms race with China. China and the US sought allies for the approaching confrontation. The US expanded diplomatic efforts with India, Australia and Japan within the Quadrilateral Security Dialogue (Quad). Meanwhile, China expanded its influence over its direct neighbours through the Shanghai Cooperation Organisation, the Asian Infrastructure Investment Bank and deepened bilateral trade. It established a 'cordon sanitaire' spanning its immediate neighbours and Central Asian states, including the now pacified Afghanistan. This was done with the help of Russia, which still hopes to be seen by China as an equal. The Chinese Belt and Road Initiative and investments in the developing world helped to build international goodwill and, more importantly, leverage.

Global power transitions have taken place since nation states have been able to exercise disproportionate influence on their neighbours and the wider world. Transitions have taken place from the 1500s onwards, – orchestrated by both regional and global powers, with demographic, economic, political and military might, and the ability to organise the global economic system. Examples include the Dutch, British, and US empires. As argued by the *Thucydides Trap*, emerging powers often engage in war with the incumbent power during periods of geopolitical instability, until a new equilibrium in the form of a regional or global order is formed. Nonetheless, some power transitions, particularly those occurring since World War II, have been largely peaceful.	**Historical Analogy**

Despite its international reach, China's dominance over its own backyard remained incomplete in the late 2020s. The Quad countries, plus the Philippines, Indonesia and Thailand, now known as Quad+3, allied with the US to resist China's expansion of maritime control near their shores. Trade dependencies prevented a war, but tensions continued to mount. While its 'nine-dash line' remained contested, China succeeded in its long-sought, largely peaceful reunification with Taiwan. This triggered formalisation of the Quad+3 in 2030 and proxy conflicts emerged throughout south and south-east Asia in the following years. Into the 2030s, Australia actively contested Chinese influence and secured sea lines of communication for its growing hydrogen exports, while reducing Chinese investment in critical industries and real estate at home.

Meanwhile, Europe struggled to redefine its geopolitical role with the US' shifted attention to the Pacific. North-west Europe looked to the US, while south and south-east Europe leaned towards China. There were too many competing interests, and too little societal and political support for continued European unity. In France, the Netherlands, Italy and Poland, polarisation and populist parties hollowed out the liberal democracy ideology. Mistrust in mainstream media was deepened by social media disinformation and did not recover. Support for democracy evaporated as citizens no longer felt represented by mainstream political parties. 'Us vs them' sentiments became commonplace at all levels of European society, regarding all sorts of issues. Throughout the 2020s and then into the 2030s, structurally high inflation, indebtedness of southern member states, discord over Europe's ability to absorb irregular migration flows, disagreement about and the inequalities of the energy transition chipped away at societal cohesion.

Societal support for the energy transition in the EU began to wane as the 2030s set in. Too many groups in society felt crossed in their rights, and more importantly, robbed in their wallets. Divisions between rural and urban, rich and poor, and liberal and conservative citizens drove NIMBYism against top-down plans for large-scale renewable electricity generation and unequal adoption of low-carbon energy measures. This, in turn, amplified broader socio-economic inequality. In response to growing societal discontent, politicians already adjusted their commitments to both nuclear energy and rigid decarbonisation. Germany and the Netherlands are now 'in' for modular reactors. REPowerEU and Fit for 55 were challenged and ultimately disregarded.

Towards the end of the 2030s, the Western liberal order was directly opposed by China's economic, political and military might. China targeted applicability of institutional arrangements and 'Western' values such as individual rights, by demanding revisions to the WTO and the UN Universal Declaration of Human Rights. By 2040, state capitalism and collective rights have become normalised in international political discourse. While fiercely opposed by young Western political elites, their eroded power base leaves little room for contest.

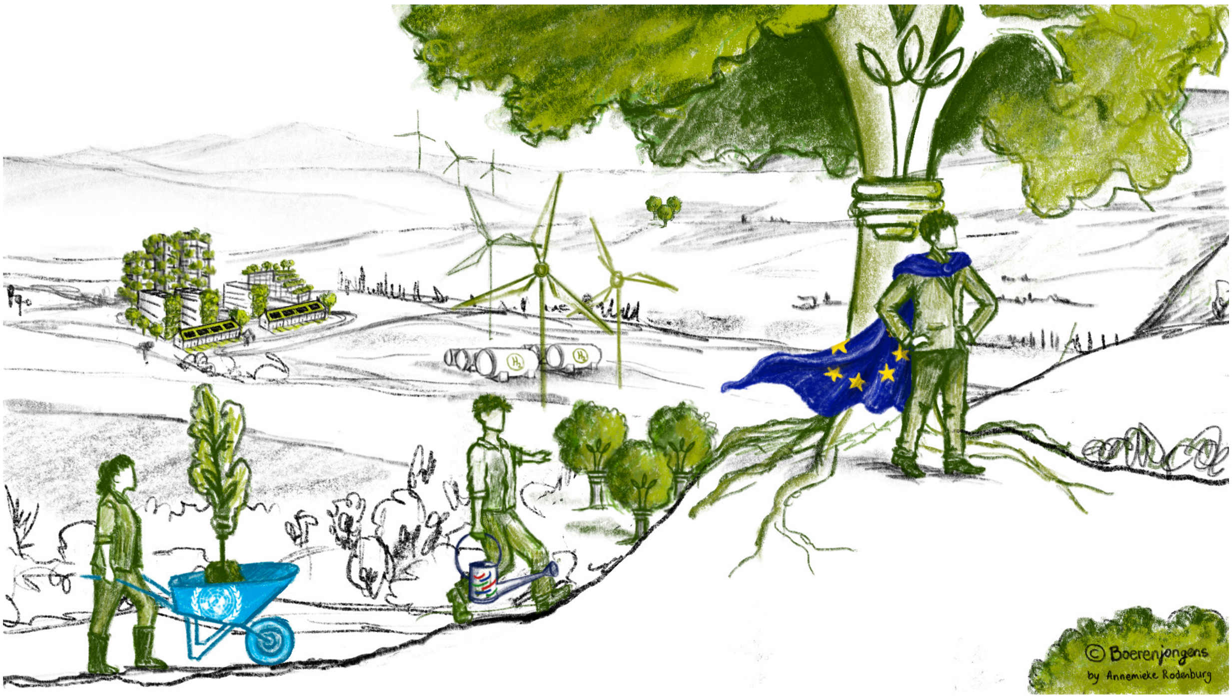
Protagonist	The CEO of a Chinese state-owned energy company celebrated the public unveiling of an ammonia storage and conversion facility in the Port of Rotterdam, hailing the latest investment as the dawn of a new era in China's engagement with the world. The other players in the new value chain were spotted sitting gleefully in the audience. The ammonia – shipped by a fellow Chinese SOE, from a majority Chinese-owned solar-to-ammonia plant in Mauritania – is designated for a newly refurbished Chinese steel mill in the Rhine-Ruhr. This is the economic geography of the 2030s.

The global turmoil increased the uncertainties in the hydrogen value chains. With the focus on geopolitical power struggles, climate change mitigation was de-prioritised; state support for hydrogen in the West – essential in the first phases of value chain development – had been erratic in Europe and completely absent in the US. Consequently, while some small-scale green hydrogen projects were achieved for pilot and innovation purposes, systemic scale-up did not materialise quickly, thus condemning hydrogen's role to that of an industrial feedstock.

Ultimately, the size, scale and geography of hydrogen value chains were determined by the Chinese government and its state-owned enterprises. While vying for geopolitical power, China remained attentive to domestic calls for environmental protection and reduced pollution. The clean appeal of renewable energy sources such as hydrogen, drove adoption of hydrogen and its applications, first in Chinese and Asian markets, and eventually across the globe, but only after 2040. China remained the market leader in all renewable technology matters – including electrolysers, fuel cells and solar panels with an inverter for direct hydrogen production.

North-west Europe remained a demand market for hydrogen. The value chains for blue, and later green hydrogen and ammonia built on and developed alongside conventional fossil trade relationships, where the aims were to incrementally 'clean up' conventional energy flows. Part of its demand was met by stable, regional partners, such as Norway, Iceland, and Portugal, though a need for energy from previously distrusted partners, Russia in particular, also continued. Stabilised relations with Russia and reallocating the market's oil products and liquid natural gas (LNG) brought Asia-destined cargoes to Europe. Hydrogen flows into north-west Europe via the Port of Rotterdam increasingly followed Chinese rules, and were dominated by state-owned companies. Investors from the Gulf and China acquired majority shares in major incumbent players in the Port of Rotterdam. The overall standing of the Port of Rotterdam diminished, as natural gas infrastructure, established in the aftermath of the 2022 energy crisis, redirected flows to other key hubs such as Hamburg.

SCENARIO 3: EUROPE'S EUREKA



A post-energy crisis 'rally around the flag' united EU member states, as they realised that to compete with the world visions promoted by China and the US, the collective European identity had to be more pronounced. They doubled down on the European Green Deal and REPowerEU to promote a whole new way of life throughout the 2020s. Reducing energy dependence on Russia through strictly enforcing sanctions was central to this. This unity rapidly turned the EU into an influential agenda-setter; and was only possible thanks to domestic trouble in larger geopolitical centres of power such as China and the US, and to newfound access to critical raw materials.

European energy-intensive industries successfully transitioned to more sustainable processes in the absence of cheap Russian resources during the energy crisis of the early 2020s. The EU's Global Gateway, the global plan to stimulate investments promoting democratic values abroad, took off and outpaced China's Belt and Road Initiative in numbers and value of projects. By the early 2030s, Europe had aligned developing countries to secure minerals and raw materials critical for accelerating its energy transition. This was made possible by other demand centres opting for different transition pathways as Europe's surge in demand for liquid natural gas (LNG) had driven up prices significantly. For example, China re-opened its coal-fired power plants.

The EU's transition-oriented political shift was built on the earlier success of Volt, Europe's federalist political movement. The unusually high turnout of young voters in recent elections stimulated a regional drive to achieve climate neutrality without furthering socio-economic inequality and injustice. A newly elected Democratic president in the US, together with a historic swing of the Senate and US Supreme Court towards the blue party, reinvigorated transatlantic relations.

Protagonist	"*10 years ago we could not have even imagined the technological progress we have achieved in rebuilding and creating a sustainable society after the energy crisis*" proclaimed the European Commission's President, a former leading climate activist. "*This is largely thanks to the political commitment of the EU and its member states, and public funding to unparalleled European research institutions*". The President's career became the metaphor for the changing times: a hard-to-achieve approach propelled into the mainstream by exponential technological progress.

While having negotiated drawdowns in the Asia-Pacific region to stabilise relations with China, the US maintained military primacy. The US dollar remained the primary reserve currency, but the Chinese Renminbi rapidly gained on other currencies. New international value chains with the Gulf, Australia and Chile supported India's rapid growth in energy demand, while effectively eliminating the conflict with Chinese and Russian interests by partnering with their state-owned enterprises.

After suffering the cost of sanctions and loss of its interdependence with Europe, Russia established new security guarantees for Ukraine, accepting the long and difficult procedure for Ukraine to join the EU, in exchange for a moratorium on it joining NATO. Robust diplomacy established frameworks for cooperation among divergent world views, united under the shared objective of slowing down anthropogenic climate change.

This climate-centric vision was realised by a new class of leaders, raised in the aftermath of the 2008 financial crisis and the 2020 COVID-19 pandemic. They sought to build on the EU's Fit for 55 plans, with ambitious decarbonisation goals to further reform energy-intensive industries and sectors. Sharing and circular economy principles took over from consumerism and materialism, elevating the collective over the individual.

Shared values of the emergent European business and cultural elite generated a sense of unity not experienced in Europe for decades: the European Hydrogen Backbone now underpins a new pan-European vision embedded in infrastructure creation. A web of refurbished and extended natural gas pipelines now weave through Europe, bringing together renewable energy-rich parts of Portugal and Spain to booming industry in northern Italy. The Port of Rotterdam retained its role as a global throughput leader and became the hydrogen derivatives entry point for the Rhine-Ruhr region, for imports from the North Sea and from around the globe. In turn, the Amsterdam-Rotterdam-Antwerp (ARA) region became the main pricing centre and delivery point for hydrogen carriers, with a highly liquid ICE Hydrogen Futures contract overtaking the Dated Brent contract in late 2030s.

The Progressive Era in the US, between 1896 and 1916, was a period dominated by social activism and political reform aimed at offsetting the problems brought about by industrialisation and urbanisation, as well as the corruption and monopolies that came with it. At first, the bottom-up movement focused on local governments and institutions, but eventually grew to state and national levels. There, it propelled democratic and technocratic ideas into social, political and economic governance. Changes included voting rights for women by passing the 19^{th} Amendment in 1920, establishing the Food and Drug Administration (FDA) in 1906, adopting scientific management (Taylorism), cooperative banking in 1908 and the Federal Reserve System in 1913.	**Historical Analogy**

Supranational CO_2 abatement policies stimulated the transfer of capital towards technologies and industries with lower emissions. In the Netherlands, farmers emerged as prominent energy players by adapting some land use from agriculture to solar and even onshore wind generation in the wake of the nitrogen crisis. Adopting viable business models for circular agriculture and small nitrogen-ammonia converters at farms reduced nitrogen emissions from agriculture to zero, finally neutralising a toxic debate between farmers, environmental groups and the government. Combined with offshore wind in the North Sea and driven by rapid technology advancements in electrolysis and fuel cells, disrupted fossil fuel-dependent industries re-emerged in a new hydrogen-powered form.

This progress, however, did not come cheaply: the price was paid elsewhere. Developing countries dubbed Europe's new approach as *green colonialism*. African, Latin American and Asian states serving as ground zero for extraction, continue to reel from the exploitative arrangements made with foreign, often European companies. The trickle down of direct foreign investment was diverted through corruption, and civilian resentment began to brew. Diverting critical raw materials at low costs enabled Europe's transition, but meant that development slowed in countries already lagging behind.

Tensions also emerged with the intentional laggards of the new economy – enterprises and states who promised to be the 'last ones standing' in the fossil-led economy of yesterday. Nonetheless, the EU, US and China agreed to jointly patrol key maritime bottlenecks such as the Strait of Malacca and the Gulf of Aden to secure supply chains. Meanwhile, hydrogen prices have stabilised thanks to the large number of exporters and a fluid financial derivatives market enabling price discovery, and risk warehousing and transfer.

Transatlantic technology policy alignment accelerated key transition technology learning curves and exponentially drove down production costs. Liquid natural gas (LNG) cargoes secured in innovative long-term contracts formed a key energy price stabiliser enabling the transition to continue. This was necessitated by persistent seasonal droughts that incapacitated European hydro, nuclear and gas-fired power plants with lower levels and warmer water.

Faster-than-expected cost reductions in electrolyser and fuel cell technologies in the late 2020s propelled hydrogen into wider use – capturing personal mobility, public transport and trucking. While industrial batteries had become competitive, slow legislation delayed renewing and expanding transnational electricity grids in north-west Europe, requiring a dual-carrier system with hydrogen. Demand for hydrogen and hydrogen derivatives grew rapidly. A prevalent liberal economic order meant a globally traded market was established early in the expansion phase. This was secured by offtake agreements and take or pay contracts with confident distributors based in the Port of Rotterdam. Institutional investors sought out hydrogen projects to participate in the EU Taxonomy. A leading traded carrier had not emerged by 2040, as various socio-technical challenges constrained system-wide roll out. Hydrogen trade was hampered by logistical constraints with toluene, while ammonia was not shipped inland because of public resistance and safety concerns.

Early indicator pointing to the world heading towards this scenario	The European Commission has elevated its sustainability priorities in response to Russia's invasion of Ukraine with REPowerEU, to accelerate the EU's key decarbonisation goals. While member states have divergent views on the transition pathways, the EU has sought to position itself as a political leader in climate policy. The EU's ambition serves as an early indicator for Europe's Eureka, now pending the crucial step of the EU's ability to match its aspirations with the means to achieve them.

Reports published by the Intergovernmental Panel on Climate Change show an exponential shift towards meeting the Paris Agreement targets. Although they highlighted the uneven pace of transition, some countries had achieved net-zero and were moving towards negative emissions, while others continued to emit. Climate leaders embraced a diverse range of sustainable solutions, from sustainable biofuels to circular carbon, which eventually resulted in localised negative emissions. Meanwhile, the last ones standing continued to use legacy energy systems and localised price advantages to fuel their economies with cheap oil and natural gas.

SCENARIO 4: BROKEN BRIDGES

In 2024 the Republican party celebrated its victory in the US presidential election. The new leader, coming from the most inward-looking wing of the Republican party, promised to reorientate the American economy, lifestyle, and norms and values. The recent economic crisis, an energy crisis domino effect, prompted the appeal of *America First, Again!* This was only one of many events that drove the world apart in the 2020s.

The new President had swiftly acted on his 'great promises' to his supporters. His administration withdrew from the Paris Climate Agreement, levied economic sanctions against 'unfriendly' states, and established schemes for renewed fossil fuel exploration and extraction in California, Florida and the Arctic. With every new measure, the partisan divide grew deeper, narratives became more charged, and confrontations between Democrat and Republican party supporters turned more violent. When a protest in New York City turned deadly, the President declared martial law and deployed the National Guard. The following deadlock between the Federal and State governments was overshadowed only by extreme calls from prominent right-wing media figures to break-up the republic – to split it into blue coasts with a red hinterland in between.

Abroad, the President's disdain towards Europe was led with a promise to withdraw support for Ukraine, asserting that it was Europe's problem. He claimed that Europe's idealistic energy transition plans were incompatible with the US's hybrid energy policy, and consequently limited long-term export opportunities for fossil and low-carbon products from the US to the EU. Despite Russia's war in Ukraine and threats aimed at NATO partners, the US sidelined its commitment to NATO's collective defence – Article 5. Without guaranteed political and military backing from the US, long lasting negotiations between Europe and Russia began over Russia's security demands and regional stability in eastern Europe, periodic fighting flare ups kept political pressure high.

Europe was on its own, its nations drifting slowly further apart. EU and member state institutions were not adequately reformed in the aftermath of the 2008 financial crisis, and remained incapable of steering Europe through the turmoil of the energy crisis and an increasingly fragmented world. North-west European leaders viewed the transition as the ticket out of the energy crisis, but south-east European countries did not share this ambition. To stymie domestic debt crises, they sought a mix of cheap Russian resources and Chinese infrastructure and electricity technology investments instead. The EU had no moral response to this, as Germany had increased imports of US 'freedom gas' to appease the US. The structurally higher gas prices that came with it drove German industry to relocate to the US under the favourable conditions set out by the country's Democratic lawmakers, which the new Republican president saw no reason to strike down.

Early indicator pointing to the world heading towards this scenario	In the midst of the Ukraine war, the passing of the US Inflation Reduction Act has had a divisive effect on transatlantic relations. Senior EU and EU member state officials denounced it for undermining the competitiveness of European businesses, pulling investments away from Europe and violating international trade rules, on the back of an already difficult period for Europe. Far-reaching, unilateral protectionist measures that impact allies, are an early indicator of the world heading towards deglobalisation and fragmentation.

While north-west Europe battled the emboldened conservatives of Europe's south-east, they neglected the urban-rural inequalities forming in their own countries. Accelerated permitting and approval processes, simplified environmental impact assessments, and shortened participatory procedures for critical infrastructure projects, boosted renewable installations, but at the cost of localised negative effects. Communities, already disenfranchised, now also felt the disproportionate burden of the energy transition. As renewable energy production remained insufficient, this only reaffirmed the views of the 'rest', that European capitals had lost touch with their rural constituencies.

Protagonist	As disgruntled citizens sought affirmation of their grievances, conservative American media pundits built on their success. One such well-off opportunist captivates underprivileged Anglophone audiences on both sides of the Atlantic with a mix of charisma and well-rehearsed oration. He missed no chance to feed on the resentment – after all, anger does wonders for the ratings. Viewers are doused daily with a combination of anti-immigration and anti-social welfare narratives, with sprinkles of militant vigilantism and political opponent discreditation in between. Comfortable to do this with European audiences too, as any semblance of civil public discourse had vanished there as well.

Despite the EU's and north-west European states' inability to revitalise stagnant industrial environments and calm disgruntled populations, the EU pushed ahead with its Carbon Border Adjustment Mechanism (CBAM) according to pre-energy crisis plans. In the late 2020s, importers of non-EU produced iron and steel, cement, fertiliser, aluminium and non-renewable energy had to pay an incremental financial adjustment in line with the internal EU Emissions Trading System (ETS) carbon price. However, as energy-intensive industries permanently scaled down production during the resource-gap caused by the global energy crisis, CBAM had little domestic industry to support.

Most renewable energy technologies – wind turbines, solar panels, electrolysers, fuel cells, batteries – and their components, were still produced in China. While export of these had long been a priority, around 2030, China's Dual Circulation Strategy was firmly established. Like north-west Europe, China was betting on the transition to stimulate its stagnating domestic economy and entrepreneurial environment, but unlike north-west Europe, it had secured raw material access ahead of time. On the back of renewable and nuclear energy, China strove for energy independence and lower carbon emissions after its CO_2 peaked in early 2030s, and was heading towards carbon neutrality in 2060. China's export of refined materials and manufactured products to Europe declined, benefiting its own domestic market, and drove up the prices in the EU. Combined with its weakened industry, the EU was unable to attract investments in the tipping point of the energy transition.

The pre-COVID-19 era of *just-in-time* efficiency was replaced by a period of *just-in-case* creative disruption in the later 2020s. With domestic troubles and disrupted global value chains, north-west Europe responded by innovating with alternative materials, improving resource efficiency with additive manufacturing, intensifying trade contacts with other resource-rich countries, and accelerating the move towards the circular economy. While there were optimistic outlooks for volumes of rare earth metals and materials that could be obtained, recycled or redirected towards renewable energy technology production, the process changes required did not occur in time. This put a hard and fast production cap on north-west Europe's manufacturing and, thus, a halted the European energy transition.

At the same time, the CBAM backfired for the EU, having been labelled as *unjust* by developing countries. In their opinion, the CBAM made them pay to avert a climate crisis for which they have little responsibility. Discontent in Latin America, Africa and Southeast Asia extended to goods and commodities not impacted by the CBAM. Rather than exporting their valuable materials to Europe, they sought trade and FDI partnerships with the US, China and India.

The absence of accepted standards often empowers brokers who can navigate the uncertainty in search of arbitrage. These are often non-state actors, such as criminal networks and armed groups. During and after the Cold War, organised crime groups worked with and for Soviet, and later Russian governments to procure foreign technology, take advantage of Western capital markets to conceal wealth, and build political influence abroad. Similarly, US intelligence services recruited the Sicilian Mafia in the US during World War II to plan, execute and consolidate their invasion of Sicily. Within the larger *Operation Underworld*, the US government worked with Italian and Jewish organised crime between 1942 and 1945 to prevent sabotage of naval ports, curtail labour union disruption, and reduce theft of military supplies.	**Historical Analogy**

By the mid-2030s, it became clear that the EU's all-in transition bet has demolished one bridge before building the next. Its foreign climate policy has failed, north-west European industry is fleeing, member states cannot affordably source the materials needed for a successful transition, and there is little public support for the decisions made. North-west Europe focused on all that was left – further specialisation in financial and digital services, and significantly decreasing energy demand, especially as circularity began to pay off towards 2040. In the absence of coordinated international leadership, globally aligned decarbonisation and climate change adaptation faltered. Emission reductions from Europe and China were offset by US commitment to fossil fuels, roaring emissions from India, and rapidly growing sub-Saharan African and Southeast Asian economies.

In this context, regional hydrogen value chains were only forming in Europe and Asia. In Europe, this market started to materialise just after 2030 but struggled to scale-up. Heavy industry relocation out of north-west Europe came at a time when further electrification was difficult. Regional green hydrogen production capacity, realised with these industries in mind, was then reallocated to other functionalities. These were primarily aimed at lowering emissions from heat and power generation by blending hydrogen in with natural gas. In Europe, hydrogen was being transported via existing onshore infrastructure, with limited shipping of hydrogen and its derivatives. Over time, the Port of Rotterdam lost its energy hub position, as fossil fuel flows decreased while hydrogen flows did not reach anticipated volumes. As industry relocated out of the Rhine-Ruhr region, the integrated value chains within the Port of Rotterdam's industrial cluster started shrinking.

In East Asia, the industrial market expanded after 2030 but scaled up quicker to outsize Europe's demand. Geographic constraints and the distances between potential suppliers, such as Australia, and large users such as Japan and China, encouraged hydrogen and hydrogen derivatives shipping to take on more serious forms. The ports of Singapore, Tokyo and Sinopec Zhongke Refinery Port in Guangdong, China, became large hydrogen import and trade hubs.

7 IMPLICATIONS FOR HYDROGEN MARKET DEVELOPMENT

In the previous chapter, we presented four diverse geopolitical and societal scenarios for the ARRRA region. Here, we will elaborate on the specific hydrogen markets that could emerge within each of the four future worlds sketched. We also reflect on the implications for positioning the Rotterdam port-industrial cluster and is constituent parties, within each of these four scenarios.

To get a sense of how future hydrogen markets might develop within the parameters of the four scenarios, we have drawn from existing theories of market development and organisation. These theories describe the various stages that markets tend to go through:

i) innovation & introduction;
ii) expansion;
iii) maturity;
iv) stagnation or renewal and transformation.

The theories also focus on the behaviour of and interactions between different market participants, as well as the nature and characteristics of traded commodities and products (*Product Life Cycle Theory*). This influences the costs of transacting and dependencies between parties in different stages of market development (*Transaction Costs Theory*).

The diverse backgrounds and strategic resources of market participants influence their future opportunities and position in the hydrogen market (*Resource-based view of economics*). What complicates thinking about hydrogen market development is that this will almost certainly be a complex process. Processes of technology innovation are non-linear, uncertain, unpredictable, and potentially disruptive. This means that theories that describe how complex systems evolve over time, and how transition management can be applied to guide this process of systems change, are also relevant (*Complexity Theory* & *Transition management*).

We use these theories to systematically consider how the critical hardware[74] and software factors[75] that were identified in chapter 3: Key actors and key factors, might co-evolve under different future investments to form a scenario-specific hydrogen market. Based on the different combinations of hydrogen products, technologies and infrastructures, different roles for market actors, and different

74 For example: infrastructure, production, processing and conversion facilities, and technologies

75 For example: behaviour of market participants, type of transactions in the market, policy, rules and regulations, norms and standards

forms of market organisation that may arise, we suggest an evolution in the position of hydrogen in the energy system, distinguishing two phases: pre-2030 and post-2030.

For an overview of the particular characteristics of each of the four markets, see Table 7.

	Revival of Rhineland Model	The Right of Sun Tzu	Europe's Eureka	Broken Bridges
Value drivers	Affordability & pragmatic sustainability	Energy security	Energy security & absolute sustainability	Absolute sustainability
Transition pace	Prolonged start, acceleration after 2030	Forced and continued acceleration	From small inventions to exponential acceleration after 2030	Fast start halted after 2030, only to recover after 2040
Hydrogen demand side	Energy-intensive industry	Energy-intensive industry and energy provision	Energy-intensive industry, energy provision, transport & mobility, and built environment	Energy-intensive industry decreased in size
Hydrogen supply side	Regional production: low	Regional production: high	Regional production: high	Regional production: moderate
	Import: high	Import: moderate	Import: high	Import: low
Technology innovation & use	Proven and tested technologies in blue and green hydrogen production, conversion and transport	Innovation in and uptake of improved blue, green and (modular) pink hydrogen technologies	Innovation in and uptake of novel diverse green hydrogen technologies	Failed innovation and uptake of diverse (green) hydrogen technologies
Geographical investment	Global market	Transatlantic market (trade blocs)	Global market	Regional market
Value chain variety	Low	Moderate	High	Low
Impact of chosen energy policy priorities on system values	**Energy security:** low-moderate Continued strong international dependency, optionality for diversified imports	**Energy security:** moderate-high Undiversified imports & regional security of supply measures	**Energy security:** high Diversified imports and regional security of supply measures	**Energy security:** low Diminishing imports and a failure to upscale regional production
	Affordability: moderate Increase in costs, but redistribution so that the large majority of society can continue to afford energy	**Affordability:** low High energy costs coupled with overall increases in costs of living result in increasing inequality and poverty	**Affordability:** high Energy costs eventually decrease with technology innovation, efficiency gains, and upscaling	**Affordability:** low High energy costs coupled with overall increases in costs of living result in increasing inequality and poverty
	Sustainability: Low-moderate CO_2-neutrality only reached towards 2060/2070	**Sustainability:** moderate CO_2-neutrality possibly reached in 2050, likely towards 2060	**Sustainability:** high CO_2-neutrality reached in 2050 (systemic change)	**Sustainability:** high CO_2-neutrality reached in 2050 (decreasing demand)

TABLE 7. MARKET CHARACTERISTICS DERIVED FROM EACH SCENARIO

This chapter also shows the expected S-curve for each market development scenario. These S-curves are summarised in the following figure.

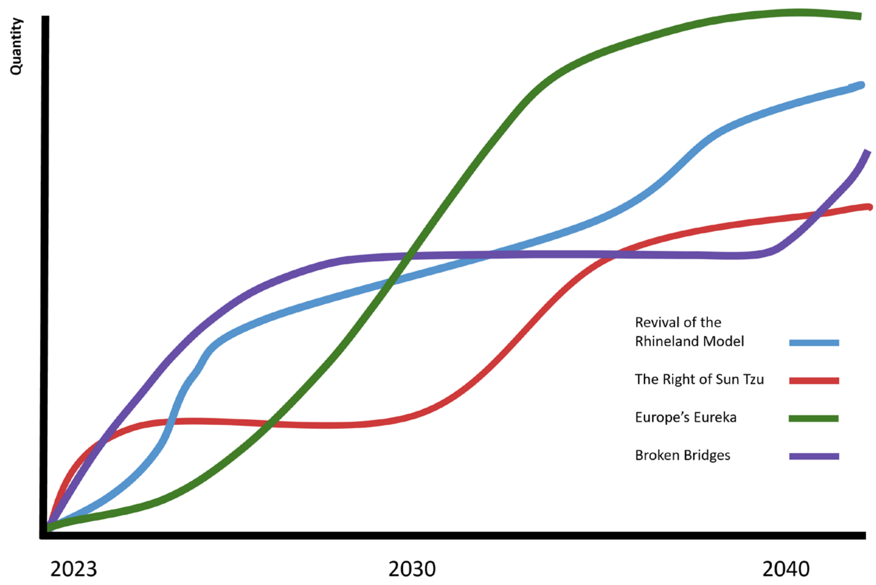


FIGURE 5. S-CURVE FOR ALL FOUR HYDROGEN MARKET DEVELOPMENT SCENARIOS

MARKET DEVELOPMENT IN SCENARIO 1: REVIVAL OF THE RHINELAND MODEL

A bird's-eye view of the emerging hydrogen market in the Revival of the Rhineland Model

In the 'Revival of the Rhineland Model' scenario, early efforts to establish value chains in the ARRRA region for hydrogen and hydrogen derivatives were disrupted by political turmoil. The lack of political support increased uncertainties and transaction costs, especially for early-stage hydrogen activities. Early hydrogen market development came to a standstill. Some existing hydrogen value chains powered by offshore wind, mostly used in large-scale industries, remained in place. However, smaller-scale and more experimental hydrogen projects and assets experienced a phase of divestment or were taken over by the existing chains.

With renewed political stability and commitment to hydrogen after 2030, collaborative and pragmatic pathways evolved based on the value drivers 'affordability and availability of energy' and 'stability and continuance of industrial activities'. In this period, governments set goals, protected national economic activities, and ensured other necessary prerequisites for hydrogen adoption were met. Industry dictated the pace of the transition by making the necessary investments, gradually phasing out fossil fuels.

Increased hydrogen demand in energy-intensive industries after 2030 resulted in cost-efficient large-volume imports of hydrogen derivatives, particularly ammonia, from areas with low hydrogen production costs.

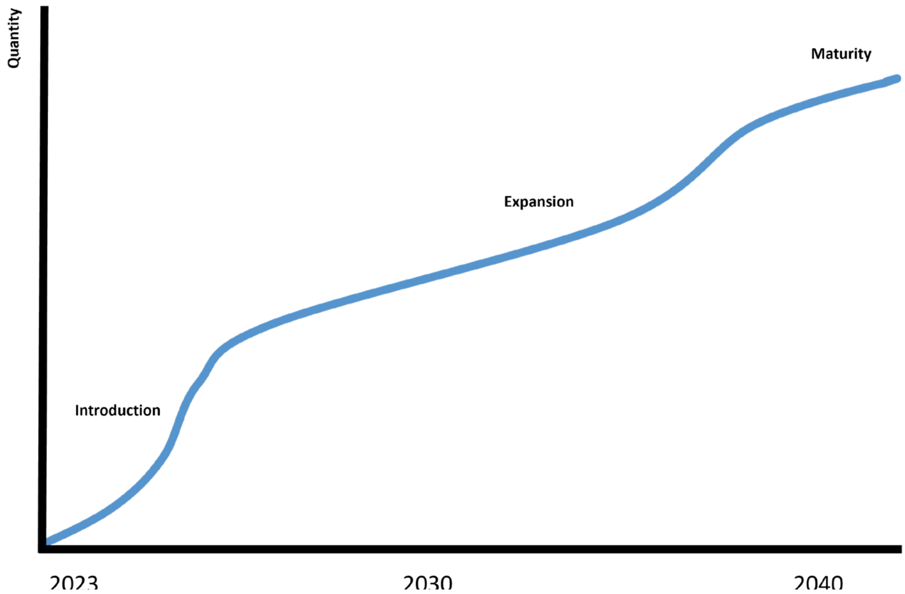


FIGURE 6. S-CURVE HYDROGEN MARKET DEVELOPMENT SCENARIO 1

Market phase 1, pre-2030: Exogenous disruption of the life cycle

In the 'Revival of the Rhineland Model' scenario, the turmoil following the war in Ukraine, including the energy crisis and its socio-economic and financial impacts, was followed by populist parties coming to power in north-west Europe. The new populist parties in charge paid little to no political attention and did not support the energy transition. Exogenous uncertainty was high, public co-funding decreased or was even completely terminated. EU efforts to establish uniform regulations on hydrogen, as well as CO_2 pricing, were incoherently adopted or undone. Furthermore, while some national pipelines were realised in and between industrial clusters, these were largely fragmented and infrastructure was far from complete. This included activities in and around the North Sea, in cooperation with UK companies. Work on fulfilling the ambition to create a coherent cross-border infrastructure network in the ARRRA came to a halt.

Hydrogen frontrunners in the ARRRA region experienced paralysis. Innovation and introduction activities initiated in the early 2030s years struggled and failed to lead to wider uptake of hydrogen in the market. Activities close to final investment decisions came to a halt. As the regional hydrogen market failed to scale up, early market participants lost their long-term perspective and many of the investments made became irrecoverable, due to sunk costs. Smaller companies with a more exclusive focus on (innovative) hydrogen technologies were particularly at risk. Those who could, merged or divested.

This stage was characterised by some companies closing down and their hydrogen technology, knowledge, facilities and installations being acquired relatively cheaply by a few larger multinational players. These were mostly the large international oil and gas companies, chemical and petrochemical concerns, with more diverse (international) activities that could accommodate low-carbon hydrogen-as-feedstock within their own business. These parties developed knowledge and experience with hydrogen value chains elsewhere. They also had cash flows to fund large-scale acquisition of hydrogen production assets and facilities in the ARRRA region. This meant they could tailor production to their own needs, and have the financial resilience to sit out this politically unstable period in Europe. Having acquired regional low-carbon hydrogen production assets and facilities, they secured their own supply. Consequently, despite the lack of political support, these industries continued to replace current volumes of grey hydrogen with low-carbon hydrogen.

However, demand for hydrogen for other functionalities or applications failed to materialise in the ARRRA region. This had direct consequences for the size and direction of international hydrogen value chains. Countries that had signed a Memorandum of Understanding or Letter of Intent with Germany, the Netherlands or Belgium decided to wait or reorient their trade interests elsewhere.

In this situation of low support and lower-than-expected demand for low-carbon energy, fossil fuel production continued operating with further funding for exploration and exploitation of new oil and gas reserves. Depending on the international dynamics, a volatile oil and gas market proceeded. Oil and gas trade with Russia saw a revival, but on a smaller-scale than before. Despite the relatively high costs, liquid natural gas (LNG) gained a much more important position in the gas market, being one of the few available options to increase supplier diversity in the short term. This was facilitated by floating LNG terminals in major ports in the ARRRA region.

Market phase 2, post-2030: Catching up, introducing and expanding the market

In the period after 2030, the hydrogen transition in the ARRRA region regained political support. Centre politicians in office showed renewed willingness to facilitate hydrogen market development even though public resources for this were limited. European governments therefore opted for intensive forms of public-private collaboration.

Governments set the transition goal and created the necessary prerequisites for hydrogen development and trade. They took renewed responsibility for further developing and operating a dedicated hydrogen backbone to connect the major industrial clusters in the ARRRA region, via publicly and privately owned transmission system operators. So, previously discrete and fragmented national infrastructures became connected. Furthermore, in large energy ports in the ARRRA region, governments invested heavily and became co-owners of conversion facilities together with energy and chemical sector companies. This considerably reduced transport and conversion costs of international hydrogen carriers for private parties.

Governments also took responsibility for implementing relatively uniform regulations, standards, and certification, including hydrogen gas qualities and guarantees of origin. Furthermore, they created incentives for energy-intensive and heavy industries (e.g., steel and chemicals), to make positive steps towards carbon-neutral high-temperature heat generation, with both 'carrots' (subsidies) and 'sticks' (stringent emission pricing and taxes). Protectionist measures were also taken to ensure these industries remained competitive in international markets. These last measures proved important in winning these parties over again, after initial failure by governments in the 2020s to accommodate the transition.

Parties with the best strategic position in the emerging hydrogen market transpired to be the established regime players who were able to buy up early-phase hydrogen producing assets and installations in the ARRRA region throughout the 2020s. These chemical, petrochemical, and oil and gas industry parties were now about facilitate the transition for others (and made quite a profit in doing so). In particular, oil and gas companies were well-positioned as they not only had relevant regional production assets, but could also rely on their experience in organising international energy value chains.

So, from 2030 onwards, industry set the pace of hydrogen adoption. A pragmatic transition path was preferred, which allowed companies to adopt proven and affordable hydrogen solutions at opportune moments (e.g., aligned with their industrial investment cycles). This implied that more affordable technologies that significantly reduced emissions eventually became preferred over expensive yet experimental technologies that operated completely emission-free, hydrogen-fuelled gas turbines, for example. While manufacturers were making strides to improve the performance of zero-emission (NOx) hydrogen gas turbines, higher maturity levels were still far away. In 2030, economies of scale and cost reductions had not yet been achieved for zero-emission pure hydrogen gas turbines. It was therefore to be expected that high-temperature-heating industrial parties will first adopt low-emission technologies operating on fuel gas mixtures, for example up to 60% hydrogen, or use electrification. These cost-driven concerns meant that decarbonisation was a much more gradual process.

To meet the increasing demand for low-carbon hydrogen, particularly for high-temperature applications, the most cost-efficient solution was to import hydrogen rather than to expand regional production capacity on a large scale. This was also because renewable electricity was in high demand for other purposes. While the hydrogen transition was delayed in the ARRRA region, elsewhere in the world interest in (international) hydrogen and hydrogen value chains remained. Notably, overseas hydrogen trade emerged over the Pacific and Indian oceans, with China, Japan, India, the Republic of Korea, Australia, parts of the Middle East and the US engaging mostly in bilateral trade. In the Indo-Pacific and in Asia, pilot projects resulted in competitive blue and green hydrogen business models. Large hydrogen producers learned enough to scale-up their production significantly – particularly in the Middle East, southern Europe, and in the US, under its successful Inflation Reduction Act. While export volumes from these regions were initially 'locked-up' in long-term (10+-year) contracts, room to offer considerable volumes of hydrogen and hydrogen derivatives on an emerging international hydrogen 'spot market' became available. ARRRA region governments supported international oil companies in procuring large volumes of hydrogen on this spot market, thereby leveraging better prices for regional industrial buyers.

Regional production in the ARRRA region remained relatively small compared to the total hydrogen supply imported. Offshore wind power in the ARRRA region was primarily used to supply electricity to end-users. Personal mobility and the built environment became largely electrified and for hard-to-electrify neighbourhoods, collective (high and low temperature) heat and biogas solutions proved sufficient. In long-distance, heavy freight transport, various forms of biofuels were adopted.

Position of the Rotterdam Port-Industrial Cluster

In this market scenario, the Rotterdam port-industrial cluster will maintain its strong import and trade hub function. It will keep its role as fossil fuel transit hub – for liquid natural gas (LNG) and other fuels – for a prolonged period of time. After 2030, the Port of Rotterdam could also become a major import and throughput hub for hydrogen and hydrogen derivatives from all over the world. Ammonia and methanol will be imported because of the relative affordability of transporting these gases. Ammonia can be stored and converted into pure hydrogen and other products in the Rotterdam port-industrial cluster. Hydrogen will also be used in the expanding biofuel industry. It is therefore likely that the cluster's chemical industry can increase in size and significance. Pure hydrogen and ammonia will be transported to other major industrial clusters in the ARRRA region, particularly Germany, via (publicly owned and operated) dedicated hydrogen infrastructure.

MARKET DEVELOPMENT IN SCENARIO 2: THE RIGHT OF SUN TZU

A bird's-eye view of hydrogen market development in the Right of Sun Tzu

In 'The Right of Sun Tzu' scenario, the ARRRA region was forced towards an accelerated hydrogen transition by continued fossil fuel scarcity accompanied by high and volatile energy prices. This initiated a period of struggle and uncertainty for the Rotterdam port-industrial cluster. In a shrinking world with ever more wars, conflicts and energy security concerns, it became risky to concentrate large-scale activities in one region. The realisation that attacks on the Port of Rotterdam could result in large-scale disruption of energy provision in the ARRRA region, energy and hydrogen derivatives systems became more dispersed and less concentrated. Due to efforts to guarantee energy security and maintain competitiveness of its energy-intensive industry, the ARRRA region experienced a strong drive towards increased domestic production of hydrogen and hydrogen derivatives. Various production methods were deployed and green and pink hydrogen and hydrogen recovery processes from industrial waste gases were optimised. These developments mainly occurred in cross-sectoral joint ventures which enabled knowledge, skills and resources to be leveraged, and development risks and uncertainties to be reduced.

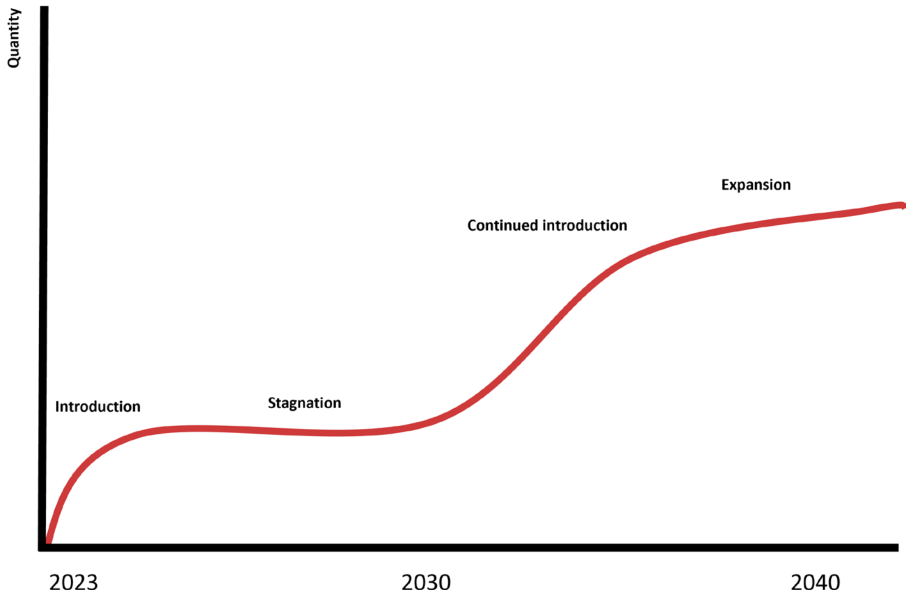


FIGURE 7. S-CURVE HYDROGEN MARKET DEVELOPMENT SCENARIO 2

Market phase 1, pre-2030: innovation & introduction phase hydrogen

In 'The Right of Sun Tzu' scenario 2, the ARRRA region progressively struggled to obtain sufficient gas and oil resources, especially as the energy relationship with Russia remained considerably distorted and tensions between the United States and China reached new and dangerous levels. The region faced a prolonged and deepened fossil fuel energy crisis. Scarcity and uncertainty led to even higher and more volatile energy prices.

High and volatile fossil-based hydrocarbon prices drove the search for more secure, stable, affordable and available alternatives. North-west Europe made it a priority to decrease its over-dependence on a small number of energy suppliers. It achieved this by:

1. working towards increasing energy import supply security;
2. accelerating innovation and introducing alternative energy carriers, with a preference, but not necessarily low-carbon energy, such as hydrogen.

As part of the first strategic priority, countries ideally steered towards diversifying supply in terms of suppliers and energy sources. However, considering the increasingly bipolar nature of the global economy, substantially fewer 'secure' trading options remained. North-west European energy policy aimed to maintain stable energy trade relations with other European partners – such as the UK, Norway, Iceland, Scotland, Denmark, France, Spain and Portugal – as well as the United States. While initial trade focused on oil and natural gas (the transatlantic liquid natural gas (LNG) market expanded and became mature, for example) this was gradually supplemented by larger volumes of low-carbon hydrogen. In ports across the ARRRA region, investments went towards dual-processing terminals, facilities and infrastructures, facilitating further diversity of supply. The ARRRA region also continued to purchase smaller volumes of hydrocarbons, blue ammonia and methanol from the Gulf states. Yet, due to the strategic position of the Gulf states in world politics and their increasingly close relationship with China, the Gulf's share of total energy supply to Europe was limited. Other long-distance value chains, especially involving the Pacific, were avoided where possible, considering the increased risk of supply chain disruptions.

Another aspect of the first strategic priority to increase energy supply security for the ARRRA region involved limiting Chinese influence over critical energy supply chains. For example, in direct energy supply chains by locating renewable energy technologies such as solar PV in Europe, and by imposing restrictions on Chinese state-owned co-ownership of European energy companies. Measures also including investing in and nearshoring indirect supply chains, for example, developing raw materials processing capacity within north-west Europe.

The second strategic priority, to accelerate innovation and use of alternative energy carriers, triggered innovation in the ARRRA region in diverse areas, including innovation for:

1. increased energy savings and efficiency rates;
2. increased efficiency, upscaling for and introducing critical renewable energy technologies such as (modular) nuclear and large-scale and offshore electrolysis;
3. circularity and energy reuse, heat and molecules, such as hydrogen, particularly in processing, refining and fuel production processes.

Hydrogen, for example, was increasingly recovered from industrial waste gases. Furthermore, carbon dioxide gained a more positive image: no longer just a waste product but an essential building block for future carbon-neutral fuels. In addition, the petrochemical industry in the ARRRA region began to invest in synthetic gas and fuel production from captured carbon dioxide and hydrogen.

Market phase 2, post-2030: from introduction to (regional) expansion

Throughout the 2030s, ongoing concerns for energy security encouraged regional hydrogen markets to expand. The ARRRA region has become a modest 'rainbow of hydrogen' producer, as it embraced green, blue and even pink hydrogen from modular nuclear reactors. The latter was increasingly adopted by Germany and the Netherlands at industrial locations.

Relatively closed regional value chains emerged based on partnerships and long-term contracts between suppliers and industrial consumers. Furthermore, industrial consumers became more actively involved in hydrogen supply chains as their struggle with insecure and expensive energy supply increased their perceived need for control. Some of the parties gained extensive experience with and knowledge of green and blue energy development and integrated hydrogen production within their own operations. But others, such as the chemical processing industry, could not take advantage of such expertise. Instead, they engaged in joint ventures with large energy companies in the petroleum, gas and electricity sectors who did have the necessary strategic skills and experience, for example to facilitate offshore electrolysis and transport of hydrogen to shore.

Only a few parties had knowledge of and experience with pink hydrogen value chains. Again, to realise such value chains, industry parties had to leverage the knowledge of experienced parties and engage in joint ventures. Consequently the different green, blue and pink value chains became characterised by different combinations of companies with different backgrounds, partnerships, and particular organisational structures and types of contracts.

On the demand side, hydrogen was adopted mainly by industry and for providing energy. The hydrogen-as-feedstock market continued to grow as hydrogen was increasingly needed for producing a variety of synthetic fuels. Hydrogen as energy carrier also became one of the major solutions for high-temperature-heating processes in the ARRRA region. Furthermore, electrolysis and hydrogen were later applied in energy provision, as means of easily storing and transporting energy and as a source of controllable power in grid management. Hydrogen was not adopted for other functions. Instead hydrogen became the preferred solution for electrification (built environment and personal transport), collective heating, and blending green gases with natural and biogas (built environment).

Around 2040, the global balance of power shifted towards China. At the same time, the US decline resulted in a fuller reorientation towards the south-east Asian markets. In 2040, most hydrogen ‘flows’ ended in East Asian and Chinese markets, which became the largest import and trade centres for hydrogen around the world and set the trading conditions. China took the lead on hydrogen value chain integration, moving towards more global markets for hydrogen.

China also further asserted itself as market leader in matters concerning renewable energy technology, including electrolysers, fuel cells and hydrogen burners. The norms, standards, and technologies developed and adopted in the 'eastern trading block' in the earlier decades became increasingly global. The ARRRA region was at a competitive disadvantage since its products and services did not seamlessly align with these. The subsequent loss of north-west European industry's international competitiveness resulted in even more takeovers by Chinese and Arabian state-led companies. Furthermore, international value chains for hydrogen and hydrogen derivatives became increasingly controlled by Chinese and Arabian investors.

Position of the Rotterdam Port-Industrial Cluster

In this market scenario a period of struggle and uncertainty for the Rotterdam port-industrial cluster will begin. In the increasingly bipolar world, the anticipated increase in container trade does not materialise: rather, the opposite happens. In the fossil fuel era, cost efficiency and scale were important competitive advantages in maritime trade. Yet, in a shrinking world with increasing wars, conflicts, and energy security concerns, scaling up and concentrating activities in one location becomes risky. The Port of Rotterdam will lose some of its dominance as Europe's major energy import and trade hub. It will still import large volumes of fossil fuels (petroleum, biofuels and liquid natural gas (LNG)). But will also transit a substantial share of hydrogen and hydrogen derivatives, produced from offshore wind and hydrogen projects, landing these at various locations in north-west Europe.

Energy source imports will be diversified and no longer concentrated. The need for a more diverse and multi-functional infrastructure network will become apparent. Regional overseas transport will take place in much smaller vessels for which medium depth of fairways will suffice. The regional nature of the market will also demand much hydrogen be traded and transported onshore. A diverse, partly private, partly public, system will emerge based on pure hydrogen pipelines and converted gas pipelines suitable for gas mixtures of different qualities. A variety of ammonia transport routes by railway, road, and pipeline will grow between various ports and the industrial demand centres in the hinterland. Conversion of hydrogen derivatives, such as ammonia, will also occur closer to demand locations. Some of this ammonia will be used immediately in hinterland industrial clusters, but some will be converted into various molecules, such as hydrogen, within these clusters. In this infrastructure patchwork, some of the conversion, pipeline and storage capacity will be used at lower throughput rates, creating redundancies, optionality as well as flexibility and backup options. Energy system resilience will be enhanced by deconcentrating resources, diversity and infrastructure multifunctionality.

MARKET DEVELOPMENT IN SCENARIO 3: EUROPE'S EUREKA

A bird's-eye view of hydrogen market development in Europe's Eureka

In the 'Europe's Eureka' scenario, the European Union – and particularly the ARRRA region – responded unitedly to the energy crisis with an ambitious transition strategy. Social, technological and organisational innovation were key and central to this strategy. Strong government support for experimentation and roll out of successful renewable energy solutions resulted in a variety of green hydrogen value chains to emerging across the ARRRA region. These value chains included geographically diffuse, multiscale production modes and a range of users and functionalities.

Internationally, the EU succeeded in setting up large-scale partnerships with green hydrogen producers from around the world. As the leader in international hydrogen trade, the ARRRA region became the main pricing point for international hydrogen and hydrogen derivatives trade. By 2040, the ARRRA region had not only made considerable strides towards carbon neutrality, it had also succeeded in making hydrogen a main source of energy and molecules in industry. It also introduced hydrogen for domestic energy. This brought about significant social change, redistributing influence over energy provision towards prosumers, farmers-turned-energy producers, and energy communities. In this scenario, the Port of Rotterdam emerged as a main import and transit hub for hydrogen-based energy in north-west Europe.

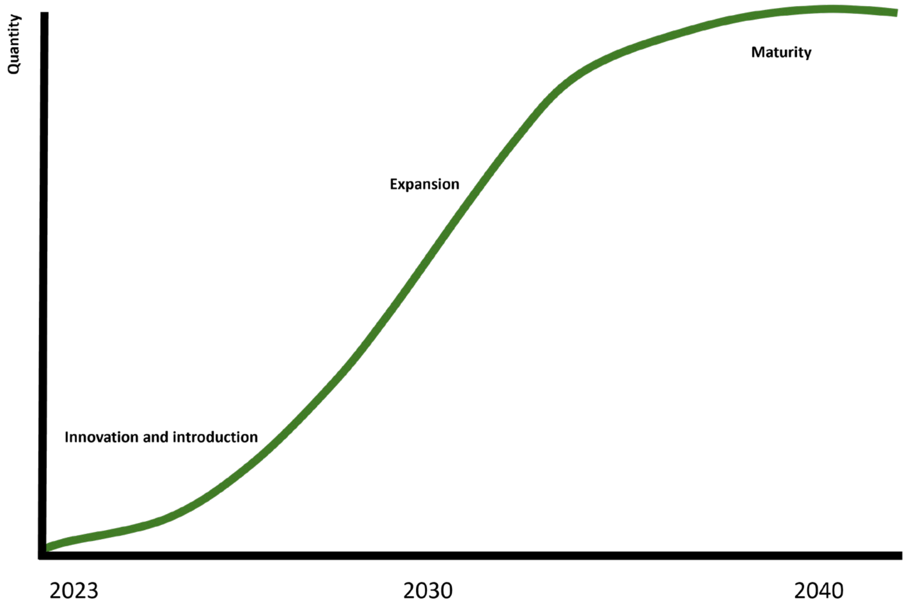


FIGURE 8. S-CURVE HYDROGEN MARKET DEVELOPMENT SCENARIO 3

Market phase 1, pre-2030: innovation & introduction phase

In the 'Europe's Eureka' scenario, EU member states responded unitedly to the energy crisis and worked together harmoniously to realise REPowerEU. For hydrogen specifically, the ambitions for 2030 were to realise 10 Mt of low-carbon hydrogen imports and to produce 10 Mt of low-carbon hydrogen within the European Union. Achieving these REPowerEU ambitions required both technology innovation and societal change.

In line with the ambition to upscale hydrogen production towards 2030, governments in the ARRRA region jointly agreed to stimulate variation and experimentation. Not just to develop the most cost-efficient solutions but also to try out a variety of possibly complementary technological, economic and societal renewable hydrogen alternatives. They established innovation niches in which new social, technological and organisational solutions could be tested.

Hydrogen valleys and existing industrial clusters in the ARRRA region became breeding grounds for experimenting on a systems scale. Here, networks of actors collaborated to test future hydrogen technologies and their integration in a wide range of energy systems, and to experiment with various business models and value chains, as well as modes of societal involvement. Actors involved in these experiments included:

- local and regional governments;
- technology innovators and knowledge institutes;
- future potential suppliers and buyers of hydrogen, hydrogen derivatives, synthetic biofuels produced with carbon dioxide and hydrogen;
- public and private storage providers and developers;
- public and private grid owners/operators.

In these so-called hydrogen niches, governments and regulators allowed actors freedom to collaborate and organise business models for hydrogen in various ways. Rather than regulating this market in a strict and uniform manner, rules and regulations were more dynamic, to match the development stage, and sometimes even context-specific. For example, exemptions on competition law were granted more frequently. Consequently, in these initial stages of niche development, a large range of collaborative formats and contractual forms arose. Market participants can choose their preferred way to minimise risks in a particular instance via 'dedicated contracting', differing per sector.

Similarly, apart from the European pure hydrogen backbone, hydrogen infrastructure development was not necessarily considered a public task. Instead, regulatory room was created for different infrastructure ownership and management structures. Requirements for this infrastructure, for example, in terms of gas qualities and gas mixtures permitted, were allowed to differ per niche or even per value chain. For example, in niches with a small number of relatively large suppliers and buyers, or niches in which hydrogen production was integrated within a particular organisation, it was considered more logical to develop private or hybrid ownership modes.

Furthermore, it made sense to integrate provision and storage infrastructure with the traditional responsibilities of public grid operators. Public ownership and operation was considered most desirable either in niches with a many smaller hydrogen suppliers and buyers, in which none of the parties had the financial means to invest in and maintain such infrastructure, or in niches where non-discriminatory third-party access was important. To enable these experimental ownership and operation modes, changes to energy market regulations were made to 'open up' the mandate of grid operators in the hydrogen domain.

All in all, regulatory and contractual flexibility, public-private collaboration and risk sharing, including (public) co-financing fostered entrepreneurial attitudes. This was demonstrated in the willingness to test potential 'regret' options in various forms of close collaboration. For innovators in hydrogen valleys, collaboration helped to significantly reduce the transaction costs associated with innovating and emerging trade in new products, technologies and services.

As information asymmetries were resolved, knowledge was co-produced and shared. This also meant that (investment risks of) conversion facilities and hydrogen and carbon infrastructures were shared by a larger group of actors. Actors could collaboratively diversify and spread their risks, which would otherwise have been impossible, especially for medium-sized organisations with homogenous asset portfolios.

To achieve upscaling of hydrogen and hydrogen derivatives import volumes, the ARRRA region made use of its own leverage and relationships as well as Europe's energy diplomacy tools such as the Global Gateway Initiative and a new EU Global Hydrogen. Via these initiatives, the ARRRA region proactively assisted new and emerging hydrogen producers to develop green hydrogen export capacity. For example, by providing co-funding and hydrogen purchasing guarantees. These efforts resulted in a considerable number of Final Investment Decisions for renewable hydrogen production in nation states all across the world, including the Gulf and the United States, but also in Chile and various African countries such as Morocco and Namibia. Towards 2030, many pilot projects were started for green hydrogen production, conversion, and overseas transport to Europe, and in particular, the ARRRA market. Pilots with diverse modes of transport were an explicit part of these emerging international value chains. Some of these were based on ammonia transport, others on pure hydrogen, liquid organic hydrogen carriers, methanol, or synthetic liquid natural gas (LNG).

Market phase 2, post-2030: expansion & maturity phases

Around 2030, the government took stronger actions to discourage the (unabated) use of fossil fuels. Large industrial emitters were targeted with very stringent carbon taxing and across the board, all forms of financial and regulatory support for non-sustainable business practices and processes were phased out. Large industry was therefore forced towards adopting completely carbon-neutral solutions, which pushed economic activity in north-west Europe towards sustainability and circularity.

By this time, it had become clear that some of the sustainable technology and business model solutions tested in niches would be more successful and scalable than others. These innovative and new ways of producing, transporting and using energy, goods and services became increasingly available to market participants outside the niches.

Within the parameters of this scenario, multiple disruptive hydrogen solutions, large-scale electrolysis had the best chance of being successful. Gigawatt-scale electrolysis became cost competitive with fossil-fuel-based energy solutions before 2030, particularly if applied in sun-lit places. Large volumes of green hydrogen and hydrogen derivatives entered the ARRRA region. However, the hydrogen market that emerged during the 2030s was very much multiscalar. Hydrogen became just as much a central as decentral solution. Hydrogen was imported and produced in large volumes, mostly for industrial and energy provision purposes, while at the same time, new and small-scale solar-to-hydrogen technologies enabled decentralised community hydrogen initiatives to develop.

The demand side of the hydrogen market also became diverse. Existing hydrogen demand remained, but multiple functionalities meant that demand grew. Hydrogen began to play a key role in personal mobility, parts of the built environment, and particularly, in energy provision. By this time, the ARRRA region had have developed a ‘double backbone’: in other words, a main infrastructure system with integrated and interacting electricity and hydrogen parts. Infrastructure was digitalised, allowing for flexible, near-real-time, responses to changes in the system. This multiscale and smartly integrated energy system that emerged throughout the 2030s in the ARRRA region contributed to system resilience.

Towards 2040, the hydrogen market reached higher levels of maturity. At this point, governments refocused their attention to regulation, monitoring and supervising competition. The regulations enforced for the hydrogen market were more specific and stringent. Governments gradually retreated from their more active roles and positions in the market. Subsidies, co-financing and public-private risk sharing focused on the missing links. The hydrogen price increasingly reflected market dynamics. Considering its central role in international trade, the ARRRA region became the main wholesale pricing point for hydrogen and hydrogen derivatives.

Position of the Rotterdam Port-Industrial Cluster

In this scenario, the Rotterdam port-industrial cluster will retain its role as major import and transit hub for energy in north-west Europe. The current strategic resources and abilities within the Rotterdam port-industrial cluster will foster or be advantageous for innovation in new energy solutions and hydrogen and hydrogen derivatives. The Rotterdam port-industrial cluster will transition itself into an innovation ecosystem or ‘hydrogen niche’. Existing characteristics of Rotterdam’s energy terminals, including its facilities, storage capacities, and connectivity via diverse infrastructures, will prove to be a considerable competitive advantage as these can be efficiently refurbished at low cost and reused for a variety of hydrogen derivatives. The Rotterdam port-industrial cluster will use its existing facilities, reputation and energy relations to become Europe’s major ammonia bunker port. Rotterdam will be able to transform existing commitments and ongoing fossil fuel trade throughout the 2020s so it can provide capacity and space for hydrogen derivatives processing.

The current hydrocarbon activities within the cluster will undergo a drastic transformation. Some of the current industrial actors will leave the ARRRA region and locate elsewhere in the world, where energy is more affordable and environmental performance less mandatory. At the same time, new emerging industries and actors will move in and take prominent positions.

MARKET DEVELOPMENT IN SCENARIO 4: BROKEN BRIDGES

A bird's-eye view of hydrogen market development in Broken Bridges

In the 'Broken Bridges' scenario, the ARRRA region intended to take swift measures to counter the severe energy crisis the region was facing. Measures included accelerating and upscaling the roll out of hydrogen solutions. However, this was hindered by ongoing deglobalisation, with the US and China both reorienting their attention to their own domestic markets. During the 2020s, Europe appeared too dependent on the global market for critical materials, commodities and technologies. Internally, the hydrogen transition came to a halt, and internationally the ARRRA region struggled to attract significant hydrogen and hydrogen derivatives flows.

In the face of continued energy scarcity, the 2030s proved a difficult period of industrial decline, economic reorientation and reinvention for the ARRRA region. It transpired that the region only began to thrive again towards 2040 and beyond.

Within the parameters of this scenario, the Port of Rotterdam did not become a major global import and transit hub for hydrogen. Global hydrogen trade did not materialise but some regional hydrogen trade did. However, this did not necessarily require large-scale maritime transport with large tankers. Onshore hydrogen pipelines across Europe proved a more affordable and sufficient means of transport. Developing circumstances meant that the Rotterdam port-industrial cluster could only become a regional hub. Furthermore, over time, industrial decline in the ARRRA region decreased demand for hydrogen and hydrogen derivatives, and it fundamentally changed the nature and type of activities that took place in the Rotterdam port-industrial cluster.

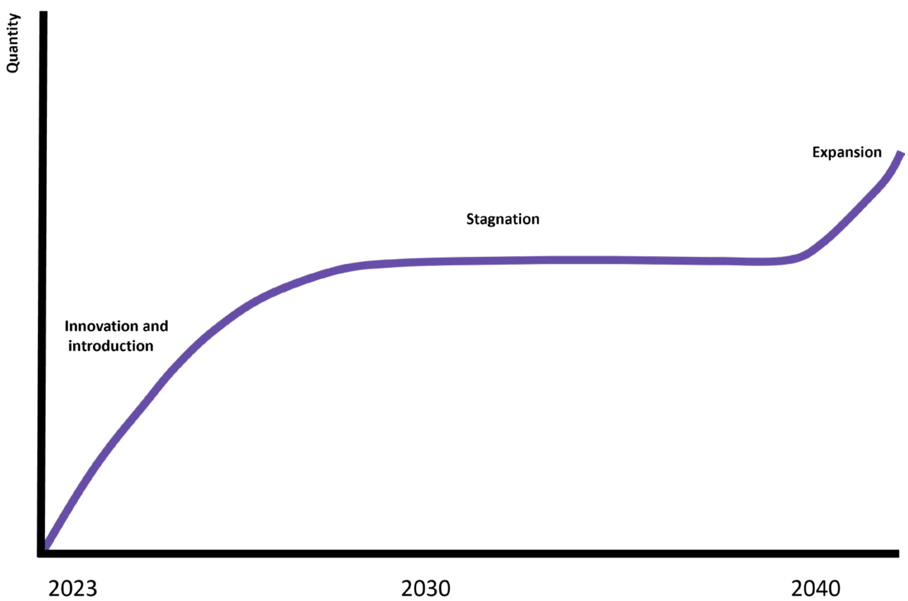


FIGURE 9. S-CURVE HYDROGEN MARKET DEVELOPMENT SCENARIO 4

Market phase 1, Pre-2030: innovation & introduction phase

In the 'Broken Bridges' scenario, the energy crisis that followed the war in Ukraine lasted for years and shocked European leaders and citizens alike. The ARRRA region was not only plagued by a prolonged energy crisis, but also by continuing high inflation rates. It was determined to find acceptable and relatively affordable alternative sources for fossil fuels and renewables such as green hydrogen. As a part of the REPowerEU ambitions, the ARRRA region accelerated its hydrogen transition. The general idea was that this would result in complementary gains for energy security, affordability and decarbonisation.

Cost efficiency became an important driver in the hydrogen transition. The idea that good decisions involve choosing the optimal solution in different functionalities resulted in relatively narrow scopes for innovation, despite the considerable funding made available. Innovation focused on realising cost efficiency gains and upscaling in times of uncertainty. When hydrogen pilots did not achieve such gains in the short term, they were terminated, and funding reoriented towards the other solutions that seemed more promising. The narrow aim of efficiency functioned as a 'fish trap', scoping out solutions in their early stages with the potential to become gamechangers later on. This, combined with high inflation and the ongoing nitrogen crisis, only allowed a modest number of projects to actually be undertaken over the years.

In addition, future market participants perceived innovation activities as much riskier due to the narrow regulatory freedom they were given. Inspired by the existing institutional design of the gas and electricity markets, and in attempts to reach clear and uniform energy laws and regulations, governments structured hydrogen markets stringently. Production and supply of hydrogen were considered competitive market activities, while distribution and transport were seen as non-competitive and as regulated public tasks. The development of hydrogen infrastructure within the ARRRA region was delegated to public gas grid operators, who refurbished parts of the existing gas infrastructure for hydrogen purposes and started to operate the emerging dedicated hydrogen infrastructure towards 2030 as part of their 'regulated mandate'.

The types of hydrogen these grid operators were allowed to transport was strictly regulated. This concerned relatively pure hydrogen, or, gaseous hydrogen of a particular gas quality range. Consequently, if external hydrogen suppliers wanted to gain access to the ARRRA hydrogen market, their 'product' had to be upgraded to this very particular gas quality before it could be fed into the grid. This resulted, for example, in a number of large-scale ammonia and methanol to hydrogen conversion facilities in the port-industrial clusters and at other market entrance points. Similarly, users of hydrogen had to purchase turbines and devices that could operate with this particular hydrogen quality.

Production and supply of green hydrogen were designated to take place outside of the 'regulated domain', meaning that supervision and regulation was mostly shaped by the existing competition laws. These laws and regulations were relatively strict, enabling only particular kinds of collaboration between market participants. So, competition was enforced early, in a tight and emerging market. Moreover, regulatory authorities found it difficult to gauge and understand technological innovations and commercial practices, which meant that adopting new solutions was delayed or even blocked. It is worth noting that the types of collaboration permitted under the competition policy all involved exemptions for efficiency improvements in technology.

The most important challenge of the ARRRA region's international hydrogen transition agenda became how to secure the import of sufficient processed materials for technology provision, and large volumes of hydrogen. Governments decided to collaborate, for example via joint purchasing agreements. The idea was that these joint purchasing agreements would provide considerable security to future suppliers, who would therefore feel more comfortable investing in large-scale green production and conversion facilities and transport modes. Contractually, however, this resulted in a relatively small number of (larger) contracts that reflected a relatively high level of uniformity. In other words, diversity of supply and suppliers was not necessarily promoted under this construction.

Market phase 2, post-2030: stagnation and decline of demand

Around 2030, the energy transition came to an abrupt halt. Trends that contributed to the stagnation included increasing deglobalisation and a failure to remain an attractive export market for commodity producers, partly because of the Carbon Border Adjustment Mechanism (CBAM). Europe's attempt to establish a monopsony[76] in an expanding global market therefore failed spectacularly. Europe also struggled with is its lack of access to sufficient, affordable, reprocessed materials. However, this was only a symptom of the underlying issue, aggravated by the overall lack of variety, multifunctionality, and backup of various critical system parts, which emerged as a consequence of the narrow-minded, efficiency driven transition.

76 where only one buyer exists for the products of several sellers

The ARRRA region also failed to invest in expanding its own materials processing sectors. Indeed, other regions in the world, and particularly China, always outcompeted the ARRRA region in processing, and therefore it was much more cost effective to import reprocessed materials and intermediates. As both China and the US did reorient towards their own regional markets, Europe struggled to catch up. It had insufficient technology production capacity to keep up the pace of the transition.

Furthermore, the strong focus on reusing existing gas infrastructure resulted in a hydrogen grid with a relatively limited capacity and restricted spatial connectivity. As the region was still quite dependent on natural gas, in the short term, there were not many pipelines that could be made available and converted for hydrogen transport. The restraint on early 'overinvesting' in hydrogen infrastructure therefore resulted in a lack of capacity, precisely when scaling up should be taking place. Moreover, the number of locations connected remained limited.

Furthermore, Europe's narrow and relatively absolute focus on CO_2 emission reduction, economic efficiency and on green hydrogen above other forms of hydrogen, also limited its diversity of supply. For this reason, Europe's transition and energy provision became dependent on a very specific suite of renewable energy technologies, resources and suppliers.

These are just three examples. Overall, the drive towards the 'one and best' or optimal solution for the hydrogen system resulted in lack of redundancy and multifunctionality. There were very few backup options that could be flexibly operated or adapted to accommodate energy fluctuations. In addition, user appliances were tailored to specific hydrogen gas mixtures and qualities, so they could not easily run on other types of fuels or gases. This was also the case for the established hydrogen infrastructures. Consequently, hydrogen users could not easily react to exogenous (geopolitical) or endogenous (system failure) disruptions.

A difficult period followed for the ARRRA region. Hydrogen users were unable to gain access to larger volumes of affordable hydrogen and were vulnerable to systemic shocks and price fluctuations. While innovation efforts were very much reoriented towards diversification, variation of supply, and creating redundancy, it would take at least a decade to reach workable solutions able to rejuvenate the hydrogen transition in north-west Europe.

In the absence of sufficient and affordable energy and hydrogen molecules, the ARRRA region experienced industrial decline. Some industries could simply no longer compete internationally, nor could they reorient most of their business activities to the European region. Others had the option to relocate closer to energy production locations elsewhere and did just that. Ultimately, but only after 2040, the ARRRA region did recover and found a new balance between energy supply and, albeit decreased, demand.

Position of the Rotterdam Port-Industrial Cluster

Within the parameters of this scenario, the Rotterdam port-industrial cluster will not become a dominant import and transit hub for hydrogen. Global hydrogen trade will not materialise. Nevertheless, a regional trade in hydrogen and hydrogen derivatives will emerge. But, this will not necessarily require large-scale maritime transport. Coastal shipping of hydrogen and hydrogen derivatives around the North Sea and European Atlantic coast will become an important activity. And as the system stretches far into the hinterland, onshore hydrogen pipelines across Europe will prove an adequate means of inland transport. A situation in which the Rotterdam port-industrial cluster becomes an end-of-pipe destination in the chain is therefore conceivable. In addition, over time, industrial decline in the ARRRA region will not only decrease demand for hydrogen and hydrogen derivatives, it will fundamentally change the nature and type of activities taking place in the Port of Rotterdam.

8 STRATEGIC OPTIONS

The previous chapter presented four possible hydrogen markets, each shaped by the dynamics of different geopolitical scenarios. They showed how the position of the Rotterdam port-industrial cluster in the hydrogen value chain might differ in each of these markets. This chapter presents strategic options the actors with a stake in the Rotterdam port-industrial cluster can pursue to strengthen their own and the cluster's future position in international hydrogen value chains.

The four market narratives draw attention to perceived certainties and uncertainties in hydrogen developments. Some trends seem more certain to materialise in the (near) future. For example, across all scenarios, natural gas will remain short in supply in the European Union in the coming years. Shortages and high (and possibly volatile) gas prices coincide with introducing hydrogen molecules, appliances and technologies. On the upside, this is likely to have a stimulating effect on hydrogen market development and early expansion. Yet, a large number of more uncertain developments can also be identified, such as:

- The influence of the (either changing or stable) organisation of economic and political world orders on hydrogen and hydrogen derivatives flows, internationally but also within Europe.
- The potential for a continued political integration of the European Union.
- The extent to which hydrogen markets materialise elsewhere in the world and how these impact hydrogen flows moving from and to the ARRRA region.
- The societal and political acceptance of various types of hydrogen value chains, including though not limited to (emissions in) production processes, supply chain impacts (negative external effects and risks, domestically or abroad), and types of suppliers (potentially unfriendly or politically unstable nation states).
- The success of European and national interventions in and for emerging hydrogen markets.
- The adoption pace and penetration of low-carbon hydrogen and hydrogen derivatives per sector and society-wide; also in light of the current energy crisis and the risk of north-west European de-industrialisation.
- The timely availability of stable supply of low-carbon hydrogen, including, the extent and success of hydrogen import diversification.
- The competition between gaseous and liquid hydrogen carriers and their organisational models.
- The appropriateness and resilience of different models of value chain organisation and regulation.

In the light of these uncertainties, we have formulated five scenario-transcending strategies to address concerns across all or most scenarios. These are the more robust no-brainers that the actors involved are advised to consider at the very least. We have also formulated three scenario-specific strategies, these are strategies that work in two scenarios but not in all and are therefore less self-evident and riskier. These strategies may prove critical for the Rotterdam port-industrial cluster's future positioning in more uncertain and disruptive futures. However, they may equally backfire if events move in a more steady and constant direction. Table 8 shows a summary of the strategies.

SCENARIO-TRANSCENDING STRATEGIES

Implementing the strategies will require active effort from a range of stakeholders. Coordination and collaboration, will be key if the Rotterdam port-industrial cluster is to maintain its position and thrive in an increasingly uncertain world. The following section identifies particular strategic paths for the various stakeholders to take.

	Strategy	Revival of the Rhineland Model	The Right of Sun Tzu	Europe's Eureka	Broken Bridges
1	Significantly expand regional production of renewable electricity and hydrogen	X			
2	Diversify imports in terms of suppliers, energy sources and carriers	X			
3	Invest in optionality and multifunctionality of terminals, conversion, storage, infrastructure and machinery	X			
4	Invest in backup and redundant energy production, conversion, storage and infrastructure capacity	X			
5	Double down on circularity	X			
6	Replace current grey hydrogen use with low-carbon hydrogen and fully embrace the transition in other industrial segments	X		X	
7	Increase investments in and control over strategic transition resources		X		X
8	Collaborate with other ports in the ARRRA region on import and trade of hydrogen and hydrogen derivatives		X	X	

TABLE 8. STRATEGIC OPTIONS WITH RESPECT TO THE FOUR SCENARIOS

Strategy 1. Significantly expand domestic production of renewable electricity and hydrogen

The four scenarios highlight that security of supply cannot be taken for granted in an increasingly uncertain geopolitical environment. In each scenario, active measures from all actors along emerging hydrogen value chains are required to reach comfortable supply level security in the ARRRA region.

One of the most important measures to increase security of supply is to significantly expand electricity generation capacity in the ARRRA region. Current political and market conditions seem to adequately stimulate large-scale investments in renewable energy projects. However, the developments required may not yet be happening at the necessary pace.

To increase the adoption rate of renewable energy and to stimulate large-scale electrolysis for hydrogen production, several initiatives at European and national government level are currently being explored or piloted. Speeding up permit and planning procedures, for example. When implemented on a larger scale, these types of measures can significantly help project development processes.

However, even if these measures prove successful and generation capacity is expanded swiftly, there is still the urgent challenge of absorbing the electricity produced in the system. An increase in variable domestic electricity generation will therefore also require developing supporting infrastructures. In this, a balance must be struck between the necessary expansion of high-voltage electricity infrastructure and the coordinated development of large electrolysis capacity and hydrogen conversion, storage and transport facilities. Despite the fact that large-scale electrolysis has not yet been technologically tested nor is it commercially viable, it seems logical, particularly for future hydrogen producers and grid operators to proactively invest in it. The electricity infrastructure is already under considerable pressure and creating new onshore high-voltage routes is not without challenges either. Diversifying supply also makes sense, considering the mixed composition of future demand, some of which will be for molecules such as hydrogen. Last but not least, considering the serious space limitations in the Rotterdam port-industrial cluster, it is unavoidable that a significant part of its renewable energy demand will be produced elsewhere. Conversion into molecules, such as hydrogen and hydrogen derivatives, provides a necessary prerequisite for transporting energy to high-demand centres.

There are caveats. Firstly, our scenarios show that investments in hydrogen technologies are not without risk. Especially if insufficient or erratic political support is granted, there is a real risk that hydrogen demand in the ARRRA will fail to materialise in the coming years. For the Rotterdam port-industrial cluster's first movers in large-scale electrolysis, high levels of control over the value chain are advisable. Vertical integration, in which an organisation's initial hydrogen production is tailored to its initial demand, longer term offtake guarantees, and joint ventures could provide the necessary comfort moving forward.

In addition to future electricity and hydrogen producers and transporters, governments will also play an important role, for example, by removing regulatory barriers, investigating opportunities for effective offshore wind-to-hydrogen tender processes, and stimulating industrial hydrogen demand. A further recommendation in this regard is that governments should also ensure sufficient consideration is given to developing and refurbishing onshore and offshore infrastructure. This requires a strategic national plan for reuse of existing natural gas assets in the North Sea, such as depleted gas fields, pipelines, and drilling platforms. For this, collaboration with the coastal states, the UK, Belgium, Denmark, Germany and Norway, as well as the current oil and gas companies active on the North Sea will be indispensable.

Strategy 2. Diversify imports in terms of suppliers, energy sources and carriers

Emerging international hydrogen supply chains are vulnerable to supply disruptions. Foreign assets may end up 'stranded' due to geopolitical or trade barriers. Supply concentration or intensification increases the impact of disruptions on operational processes. In other words, a strong dependency on one or just a few suppliers of hydrogen and hydrogen derivatives and supply chains is not recommended.

Future hydrogen importers and users, such as large industrial parties in the chemical, steel, refining and transport sectors, should diversify supply as they become more focused on hydrogen activities. By the time hydrogen markets enter the expansion phase, future hydrogen users should have already established a diverse portfolio of contracts with a balanced reliance on multiple suppliers and supply chains. Furthermore, as our scenarios highlight, some investments will prove more robust across all the scenarios. These include investments in hydrogen activities in the transatlantic basin and the European Union, while others will prove riskier, such as some locations in parts of Africa, Asia, and the Middle East.

A balanced portfolio of activities across the globe will be key to spreading risks and minimising the impact of supply disruptions on operational processes. This will also provide opportunities to experiment with and learn from setting up different types of hydrogen value chains and their associated contracting practices. Expanding towards the United States, benefiting from regulatory initiatives and stimuli such as the Inflation Reduction Act, the Middle East, and potentially even Asia, may help players to gain knowledge and experience and to build relationships that can be leveraged later in future European hydrogen markets.

A potential concern is that investing in hydrogen production and in trade with some European neighbours (Middle East and North Africa MENA) seems increasingly risky. However, this is a region that we cannot ignore – especially if trends such as deglobalisation further materialise. There is a role for governments in the ARRRA region to emphasise hydrogen projects as part and parcel of energy and climate diplomacy with our direct neighbours – focusing on providing security and stability, energy, water, and food in addition to hydrogen trade – perhaps even more so than with more distant future hydrogen producers.

Strategy 3. Invest in optionality and multifunctionality of terminals, conversion, storage, infrastructure and machinery

In this energy transition, there is no silver bullet or holy grail solution. Neither will it be predictable or linear. Instead, this transition will involve developing various energy solutions, on different scales and for different users, and in continuously changing circumstances with unpredictable, potentially disruptive, events.

Hence, it is critical that the actors involved in the Rotterdam port-industrial cluster do not put all their eggs in one basket. Optionality and multifunctionality at all stages of the supply chain – supply, conversion, transport, storage and use – is vital to ease transitions in future worlds in which the ARRRA region remains globally influential. Moreover, it is a necessity when navigating through those future worlds in which the ARRRA region has lost rule setting power, or where the EU ends up fragmented.

Optionality will enable parties to flexibly choose between different solutions. For example, between different suppliers, different types of energy, or even, different functionalities or industrial activities. For potential future producers of hydrogen in the ARRRA region, who rely on an abundant supply of local electricity, optionality could entail having an electricity or hydrogen import option. This will enable them to arbitrage, or choose between different suppliers. It will also provide a solution when high electricity demand forces reduced hydrogen production, the industrial users sourced by these producers will still need a continuous flow of hydrogen molecules.

For potential future users of hydrogen in the ARRRA region, and especially in the Rotterdam port-industrial cluster, optionality could simply mean flexible multi-sourcing. This implies having flexible offtake agreements, or, even better, long-term offtake contracts with flexibility clauses and real options included, allowing these parties to adapt and make strategic supply choices over time. Optionality could also mean a range of energy sources and carriers. With dual firing turbines and other technologies, for example, industrial users could choose between various liquid and gas fuels depending on price and availability.

For transmission grid operators, optionality should involve infrastructure multifunctionality. For example, new (and refurbished natural gas) pipelines for hydrogen, should be designed to accommodate multiple gases, or even mixtures of gases, such as hydrogen, different qualities of biogas (with different concentrations of methane, hydrogen sulphide, and ammonia), or even carbon dioxide. Multi-directionality of flows is also key. Such multifunctionality might be facilitated by establishing regional or national Infrastructure System Operators, in which the current segregated functions and ownership between power, gas and district heating systems no longer apply. This would make coordination easier and would reduce competition between modes of transport, thereby reducing risk and expanding opportunities for no-regret options.

For port authorities, especially the Port of Rotterdam, optionality could involve stimulating and co-investing in multifunctionality of terminals, conversion and storage facilities, as well as infrastructure. This should apply throughout and between the Rotterdam port-industrial cluster and the other industrial clusters in the ARRRA region. Leveraging existing fossil fuel positions, assets and facilities is also particularly relevant. For example, most scenarios anticipate an important role for the Port of Rotterdam in liquid natural gas (LNG) import and trade at least throughout the 2020s and into the 2030s. Investors in existing and new LNG facilities and infrastructure should make sure these are easily adaptable for handling ammonia, or other hydrogen derivatives that might also start flowing towards the ARRRA region. However, since it is uncertain that these flows will actually come to the Port of Rotterdam, it may be necessary to reduce the risk of these investments via public co-investing or other arrangements.

An important caveat with investments in multifunctionality is that these should not encourage continued fossil fuel use when, from an energy security perspective, fossil fuel is no longer necessary. That is, multifunctionality should be used to increase opportunities to adopt low-carbon energy options sooner, or more flexibly, and to gradually phase out hydrocarbon energy flows, but not as a justification for continued fossil fuel trade and use.

Optionality will only be possible if governments and regulatory arrangements facilitate a broad range of initiatives, such as experiments and learn-by-doing, as well as collaboration in the cluster.

Strategy 4. Invest in backup and redundant hydrogen production, conversion, storage and infrastructure capacity

To further increase resilience to possible hydrogen supply chain disruptions, incorporating essential redundancies in the system should complement increased optionality and supply alternatives. Redundancies are system components which are generally underused or unused, and should include backup generation, strategic energy reserves, and pipelines not used to their full capacity. These system elements can then be mobilised if regular system functions fail. Redundancy generally requires close collaboration between governments, regulators, suppliers, grid operators and even large energy users. Redundant elements can then be used, for example, for creating strategic hydrogen reserves, maintaining backup firing and generating solutions, as well as developing excess hydrogen storage and infrastructure capacity.

Redundancy might sound like an unfavourable measure, particularly because it is generally costly while its use is uncertain. However, costs are not the same as value. The optionality that redundancy provides in the event of costly disruptions should be valued and taken into account in critical investment decisions, in particular for infrastructure. Transmission System Operators should therefore adopt real-option-valuation methods or comparable approaches to properly evaluate essential redundancies in the system. Whether redundancies will be more outspoken in gas and electricity infrastructure or other components, remains to be seen. To establish a balanced system with sufficient redundancy, transmission system operators must experiment, overinvest and constantly evaluate the various infrastructures. Changes to regulatory frameworks will be required to make this happen and to socialise the costs of these activities.

Strategy 5. Double down on circularity

Currently, circular production processes do not provide solutions to some of the more pressing short-term energy and materials needs. In the long-term, increased circularity would help increase efficiency and decrease at least some of the Rotterdam port-industrial cluster's external dependencies on materials, molecules and energy. Accelerating circularity initiatives within the cluster will improve efficiency and enable critical resources to be reused.

Port authorities throughout north-west Europe are already leading the way with circular economy strategies and policies. The Port of Rotterdam would be wise to continue and even double down on its efforts to facilitate circularity activities within the cluster. For example, this could be promoted by:

- attracting new business and service providers which can support the move towards increased industrial circularity;
- continuing to align stakeholders within the Rotterdam port-industrial cluster;
- co-investing in necessary port infrastructures for an increased movement of materials, molecules, such as hydrogen, and energy across the cluster.

Considering current knowledge gaps and uncertainties, there is also a role for the Port of Rotterdam to support and help disseminate research, innovation and knowledge creation. Key aspects include efficiency improvements in collecting, sorting and processing strategic transition materials, such as platinum for electrolysers and various forms of energy.

Circularity also involves reusing heat and molecules, for example by recovering hydrogen molecules from industrial waste gases. In the coming years, it will be critical to move beyond pilot projects towards systemic and strategic application and integration of circularity throughout the Rotterdam port-industrial cluster. This will require ambitious systems and optimisation based on exploiting cooperation and collaboration opportunities, and might involve process changes for various major flows within the Rotterdam port-industrial cluster.

At the same time, the increasing physical and relational interdependencies that emerge between actors in the Rotterdam port-industrial cluster, due to increased circularity, can also lead to major vulnerabilities. These may arise when conditions in the ARRRA region, such as permanently high but uncompensated energy prices, are detrimental to the competitive position of some of these actors. Strong physical interdependencies and obligations may limit options for change or relocation. Such actors terminating their activities in the ARRRA region, voluntarily or otherwise, may threaten the continuity of other parties' businesses in the Rotterdam port-industrial cluster.

The Port of Rotterdam and governments therefore have an important role to play. They must ensure that the principles of optionality and redundancy, as discussed in the previous two strategy recommendations, are considered when developing strategies for more circular industrial processes in the Rotterdam port-industrial cluster. One option could be to scale-up circularity initiatives by including increasing inter-cluster flows of materials, some types of energy, and molecules such as hydrogen, despite this circularity having a negative impact on transportation costs.

SCENARIO-SPECIFIC STRATEGIES

Strategy 6. Replace current grey hydrogen use with low-carbon hydrogen and fully embrace the transition in other industrial segments

It is hard to predict the eventual uptake of hydrogen in volumes and across functionalities. Eventually, it is almost certain that in the chemical industry, current grey hydrogen usage will be completely replaced with low-carbon hydrogen. What remains unclear, is the pace of this replacement and the types of measures required to facilitate the chemical industry in its decarbonisation.

The arguments in favour of a swift phase out of grey hydrogen are compelling. Accelerated replacement of current grey hydrogen usage could be an important signal, and impetus, for other sectors to adopt low-carbon hydrogen. It could also be a meaningful statement towards society and governments, namely, that the sector is embracing the energy transition and is moving beyond compliance towards being a valuable and proactive partner in system decarbonisation. This message is critical. The scenarios in this report show there is no guarantee for a continued social and political licence to operate for big industry in the Rotterdam port-industrial cluster or elsewhere in the ARRRA region. Showcasing rather than talking about commitment will help convince governments to constructively engage in pragmatic and supportive sustainable industrial policy and could be a factor in public acceptance of such policies.

At the same time, however, it is important to recognise that the current energy crisis has hit the European chemical industry particularly hard. The sector is struggling and failing to remain cost competitive with producers elsewhere. Meanwhile, European chemical product exports have decreased, while imports of chemical components have increased in the past year. Because the European chemical industry generally is more environmentally conscious than other players in the sector, increased imports come with a larger carbon footprint, not just because of transport emissions.

Chemical companies are nearing 'breaking point'[77] and the lack of a clear perspective on affordability of energy in the near future is hardly conducive to additional investments in expensive replacements for grey hydrogen.

Indeed, despite popular assumptions, low-carbon hydrogen has not become more cost competitive compared to grey hydrogen or natural gas in this recent energy crisis. The costs of blue hydrogen have risen with the natural gas prices, while green hydrogen production costs have simultaneously risen with the electricity price. Such price shocks can only be avoided if hydrogen manufacturers owned renewable energy sources and produce hydrogen directly from these sources. However, such intermittent hydrogen production on its own is still very expensive, and in many cases, the technology is still in a testing phase. Therefore, very few of such 'closed production systems' currently exist nor can they be developed in the short term. To improve cost competitiveness of low-carbon hydrogen for large industries in the short term, energy prices need to decrease and technology innovation in intermittent electrolysis needs to result in cost efficiency gains.

An accelerated replacement of grey hydrogen with low-carbon hydrogen does not give the chemical industry time to wait and see whether either of these trends actually occur. Consequently, these companies are unlikely to act without guarantees and support. There is a clear conundrum: for low-carbon hydrogen to become a serious alternative for fossil fuels and grey hydrogen in the ARRRA region and to attract large import volumes, industrial demand for hydrogen must materialise soon. However, as long as low-carbon hydrogen is not an affordable, and thus serious, alternative for these conventional fuels and carriers, industry will not move on.

To overcome this conundrum, closer collaboration between government and industry is important. The industry should be a major contributor of its own solutions, however, government support is also essential. This includes providing short-term relief during the energy crisis and offering a long-term perspective on (relative) hydrogen affordability, perhaps by subsidising low-carbon hydrogen uptake and usage. A wider political and societal debate is necessary to establish the moral prerequisites of these support measures, particularly in light of potential continuing inequalities and increasing energy poverty among household consumers.

77 Cefic, October 2022. Position Paper. Energy crisis: the EU chemical industry is reaching breaking point. Available via: https://cefic.org/media-corner/newsroom/energy-crisis-the-eu-chemical-industry-is-reaching-breaking-point/

Strategy 7. Increase investments in and control over strategic transition resources

A successful hydrogen transition very much depends on availability and affordability of strategic transition materials, technologies, and skilled labour. To guarantee these resources, additional efforts might be required, particularly in future worlds characterised by trade wars, deglobalisation, resource scarcity, or a deteriorating position of Europe in global affairs.

In these future scenarios, it is particularly critical to anticipate a need for security of supply strategies for essential raw materials and intermediary products for generating renewable electricity and developing hydrogen technologies. For governments, for example, this would translate into a suite of strategic activities. Essential activities include increased diplomatic efforts to strengthen trade relationships with critical raw materials producers. In addition, governments should engage in thorough and continuous monitoring of the ARRRA region's needs for materials and technology as well as its import dependencies. Governments should then take appropriate measures when dependencies become too large, such as supply diversification or increased regional production of materials and technologies.

This is also an opportunity to prioritise north-west Europe's security and strategic strength in national and regional innovation policies and programmes regarding next generation materials and clean technologies: two technology areas in which Europe currently has a technology leadership position. Under the right conditions,[78] leadership in these areas could translate into increased international competitiveness in various sectors, economic growth, sustainability and even increased resilience. Creating these conditions in times of increasing geopolitical and economic disruption will be challenging. Protectionist measures are likely to be necessary, for example, rules that help prevent (early) foreign takeovers of small companies and their technology patents, mandating local operations, and ensuring knowledge transfer from non-European companies operating in the ARRRA region.

Similar opportunities exist for prioritising security and stability in strategic industrial policy. Especially in an increasingly uncertain geopolitical environment, the critical nature of maintaining, starting up, or reshoring relevant processing and manufacturing capacities for the ARRRA region's energy transition may justify stronger support for, or even protection of, particular industrial sectors. What sort of measures are appropriate should be determined based on an assessment of current

78 sufficient time, socio-political support, a level playing field for smaller companies in particular, and a stable and enabling innovation and introduction environment

processing capacities, sector resilience, opportunities for supply diversification, and likely critical nature of processed materials in increasingly uncertain futures.

A case in point is aluminium. Aluminium demand is projected to nearly double in Europe in the coming years, mainly because of the foreseen production increase in new cleantech such as EVs and for the expansion of power grids. At the same time, the European aluminium industry lost 30% of its primary production capacity between 2008 and 2021, a trend that is expected to be worsened by the 2022 inflation that hit Europe harder than other global regions. The European aluminium industry has also raised concerns about its own survival in the light of ongoing supply chain disruptions, high regulatory costs, and the inability to compete with under-priced, high-carbon aluminium exported by China.

It would be advisable to initiate a debate about whether and how to ensure continued availability and affordability of essential materials in Europe, such as aluminium and steel. If the outcome of this debate is that an increase in regional production of these materials is desirable, it is clear that some form of support or protection is required to enable market activities to continue or get off the ground. Obviously, this is no straightforward strategy that would work in all instances.

1. It is expensive, it places constraints on public budgets and may trigger negative public sentiments, especially when returns do remain privatised.
2. There could be a wider discussion about the desirability of protecting industries that have been struggling for some years already, for example because of stagnating demand and low-cost production elsewhere in the world. The absence of fair competition could enhance inefficient production processes and result in higher consumer prices.
3. Existing refining and processing capacity is not necessarily in companies owned by north-west European parties. But how protectionist measures might impact refining and processing companies that are owned and operated by foreign parties, particularly those from more politically sensitive countries, needs further research.
4. Increasing obstacles to free global trade can result in companies that miss opportunities for international knowledge transfers, scaling, and cross-border funding.

On a larger scale, it could risk the economic welfare and growth that north-west Europe has been experiencing as a consequence of its extensive network of stable and relatively open international trade relationships. It is important to create and use ‘early indicators’ of evolving trends to help deal with these dilemmas.

Strategy 8. Collaborate with other ports in the ARRRA region for import and trade of hydrogen and hydrogen derivatives

The Port of Rotterdam could have much to gain from close partnerships on hydrogen developments with other ports in the ARRRA region. Firstly, because the energy transition has proven to be a challenge too big to be addressed by the means and efforts of a single port, particularly for a port such as the Port of Rotterdam, which has a strong fossil fuel legacy to include in its strategic considerations. Secondly, because closer collaboration could create novel and better solutions for greater resilience of the ARRRA port system overall.

On the one hand, closer collaboration on energy in general, and hydrogen developments in particular, align well with ongoing developments in the European port scene. On the other hand, collaboration seems to remain limited to partnerships, alliances and joint ventures in attempts to realise particular projects, technologies, or infrastructures. Yet, generally, ports frame their position in a competitive game with neighbouring ports. They compete to enlarge their current and future share of liquid natural gas (LNG) and hydrogen imports, and to service larger parts of the hinterlands with transhipments, pipeline connections and other infrastructures. Such a framework prevents knowledge sharing and aligning strategic objectives with respect to regional competitiveness and energy security at a higher level.

Close collaboration might prove essential for continued security of supply and overall resilience of the ARRRA port system in future scenarios characterised by more frequent or even permanent global supply chain disruptions. Collaboration will also be needed in future scenarios where supply routes undergo considerable change, for example, because of deglobalisation, nearshoring or a successful expansion of the Chinese Belt and Road Initiative in Central and Eastern Europe. These developments highlight that there are no guarantees that renewable energy imports and trade will take place via ports with a North Sea connection, as has been the case for fossil fuel trade.

In such future scenarios, ports in the ARRRA region could benefit from a common strategy for increased system resilience. This would have to involve, for example, a shared approach to infrastructure development and optimisation, and incorporate the issues of optionality and redundancy as discussed above. It would also have to include data sharing and simultaneous adoption of new, smart technologies to enable better monitoring and coordination across ports. And last but not least, it would have to be based on some degree of intra-regional port specialisation, with ports playing to their own strengths and balancing out each other's weaknesses. For example, the space limitations for some ports in the ARRRA region are more pertinent than for others. The Port of Rotterdam is limited in space to sufficiently expand its renewable energy production capacity. It may make sense for other ports, with more land available to specialise in local production and possibly conversion of this renewable energy in various forms.

At the same time, the Port of Rotterdam has other unique geographic characteristics, such as its proximity to offshore underground storage capacity for molecules such as hydrogen and carbon dioxide. It makes sense to specialise in CO_2 capture, use and storage, though a social and political licence to operate for carbon capture, utilisation or storage (CCUS) needs to be actively pursued. Also with an established and mature refining and chemical ecosystem, the Port of Rotterdam could be more competitive than other ports for large-scale import of hydrogen derivatives as well as technology innovation, circularity and efficiency improvements on the hydrogen demand side.

Shared infrastructure development and intra-regional specialisation will generate additional interdependencies between ports in the ARRRA region. This is not a bad development as it would bring about a network effect, creating a resilient regional ecosystem in the ARRRA region. The many intertwined, and multi-directional flows of materials, molecules and energy, which are exchanged in complex value chains rather than via concentrated markets or linear supply chains, will require new forms of coordination. For this, port authorities, such as the Port of Rotterdam, will need to adopt new roles and rules. Furthermore, government support for removing barriers currently posed by existing competition laws will also be critical.

Again, these recommendations cannot be straightforwardly adopted. In future scenarios in which the global and European economic order remains characterised by relatively free and open trade and competition, the Port of Rotterdam would place itself at a disadvantage by sharing knowledge and information with its direct competitors in the region. This is potentially more worrisome for the Port of Rotterdam than for other port authorities, because arguably, due to its size and energy import history, it has more information to share than smaller or newer ports in the area.

Furthermore, increased intra-regional specialisation could result in a lower degree of diversity within the Rotterdam port-industrial cluster. This would translate into an increased dependency on others and thus, increased vulnerability, if the regional ecosystem fails. Besides, there are by no means guarantees that diverting energy and resources away from the Rotterdam port-industrial cluster's internal transition aims, towards the transition aims of the regional Port ecosystem, will pay off. The Rotterdam port-industrial cluster's own transition may be endangered as a consequence. Add to that the increased governance risks – such as the loss of control on and flexibility in implementing strategy – and the increased complexity of decision-making. It then becomes obvious that the Port of Rotterdam should move cautiously when it comes to closer collaboration with other ports in the region. Also in this case, to deal with these dilemmas, it is important to create and use 'early indicators' of relevant trends as they evolve.

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APPENDIX I – LIST OF LITERATURE REVIEWED

The literature review list was generated based on relevant academic and grey literature on hydrogen and geopolitical and/or societal implications in the last five years. 2017 was taken as a cut-off point to limit the sample, and the literature was generated using two search strings, one focusing on geopolitics and one focusing on society. The following table lists the literature reviewed in Step 3.

Item	Author or Publisher	Title	Date
1	IRENA	Geopolitics of the Energy Transformation: the Hydrogen Factor	2022
2	Fridolin Pflugmann and Nicola de Blasio (Harvard Belfer Center for Science and International Affairs)	Geopolitical and Market Implications of Renewable Hydrogen	2020
3	Nicola de Blasio and Fridolin Pflugmann (Harvard Belfer Center for Science and International Affairs)	China: The Renewable Hydrogen Superpower?	2021
4	Nicola de Blasio and Alejandro Nuñez-Jimenez (Harvard Belfer Center for Science and International Affairs)	The European Union at a Crossroads: Unlocking Renewable Hydrogen's Potential	2021
5	Nicola De Blasio and Alejandro Nuñez-Jimenez (Harvard Belfer Center for Science and International Affairs)	Will Renewable Hydrogen Help Unite Europe?	2020
6	Julian Grinschgl, Jacopo Pepe, and Kirsten Westphal (SWP, German Institute for Security Studies and International Affairs)	A New Hydrogen World: Geotechnological, Economic, and Political Implications for Europe	2021
7	Yana Zabanova and Kirsten Westphal (SWP, German Institute for Security Studies and International Affairs)	Russia in the Global Hydrogen Race: Advancing German-Russian Hydrogen Cooperation in a Strained Political Climate	2021
8	Rossana Scita, Pier Paolo Raimondi and Michel Noussan	Geopolitical implications of the future hydrogen economy	2020
9	Thijs van de Graaf (Oxford Institute for Energy Studies)	The next prize: geopolitical stakes in the clean hydrogen race	2021
10	Thijs Van de Graaf, Indra Overland, Daniel Scholten, Kirsten Westphal	The new oil? The geopolitics and international governance of hydrogen	2020

Item	Author or Publisher	Title	Date
11	Scita, Rossana; Raimondi, Pier Paolo; Noussan, Michel (ZBW, Leibniz Information Centre for Economics)	Green Hydrogen: the Holy Grail of Decarbonisation? An Analysis of the Technical and Geopolitical Implications of the Future Hydrogen Economy	2020
12	Westphal, Kirsten; Dröge, Susanne; Geden, Oliver	The international dimensions of Germany's hydrogen policy	2020
13	Linda Hancock and Linda Wollersheim	EU Carbon Diplomacy: Assessing Hydrogen Security and Policy Impact in Australia and Germany	2021
14	Michel Noussan, Pier Paolo Raimondi, Rossana Scita and Manfred Hafner	The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective	2021
15	Bob van der Zwaan, Sam Lamboo and Francesco Dalla Longaa	Timmermans' dream: An electricity and hydrogen partnership between Europe and North Africa	2021
16	G. Maggio, A. Nicita, G. Squadrito	How the hydrogen production from RES could change energy and fuel markets: A review of recent literature	2019
17	John Kerkhoven & Rob Terwel (ISPT & TNO)	HyChain2: Cost implications of importing renewable electricity, hydrogen and hydrogen carriers into the Netherlands from a 2050 perspective	2019
18	Roland Berger	Hydrogen transportation l The key to unlocking the clean hydrogen economy	2021
19	Fuel Cells and Hydrogen Joint Undertaking	Hydrogen Valleys Insights into the emerging hydrogen economies around the world	2021
20	Cedric Philibert	Perspectives on a hydrogen strategy for the European Union	2020
21	Erasmus University Rotterdam: DRIFT	Hydrogen for the Port of Rotterdam in an international context. A plea for leadership	2020
22	Linda Hancock and Natalie Ralph	A framework for assessing fossil fuel 'retrofit' hydrogen exports: Security-justice implications of Australia's coal-generated hydrogen exports to Japan	2021
23	Swetha Ravikumar Bhagwat and Maria Olczak (FSR and AEEP)	Green hydrogen: bridging the energy transition in Africa and Europe	2020
24	David Schlund, Simon Schulte, and Tobias Sprenger	The who's who of a hydrogen market ramp-up: A stakeholder analysis for Germany	2022
25	Andrew J. Chapman, Timothy Fraser, Kenshi Itaoka	Hydrogen import pathway comparison framework incorporating cost and social preference: Case studies from Australia to Japan	2017
26	Steve Griffiths, Benjamin K. Sovacool, Jinsoo Kim, Morgan Bazili and Joao M. Uratania	Industrial decarbonisation via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options	2021

TABLE 9. LIST OF LITERATURE REVIEWED

APPENDIX II – EXTENDED LIST OF EARLY INDICATORS

Scenario planning was used to gain insights into the ways in which uncertain geopolitical and societal dynamics could shape different worlds with different energy and hydrogen challenges for the ARRRA region. Subsequently, eight scenario-transcending and scenario-specific strategic recommendations were formulated. These are designed to help actors in the Rotterdam port-industrial cluster anticipate and prepare for developments that could influence their position in future international hydrogen value chains. For the scenario-specific recommendations in particular, it is important to know which strategy to adopt in which type of situation, and when to change strategies in the light of new developments.

This is what early indicators are for. These are signals of change in the major uncertainties that determine different futures. The following is a non-exhaustive list of indicators to monitor, in order of increasing specificity, starting with forces for change to global political and economic world orders (P2: Degree of global cohesion, P3: Rule setters in global markets) and moving towards the different ways in which countries protect their (energy) interests (EC3: Extent of globalisation, P4: Energy security, ENV2: Scarcity of raw materials, and ENV4: Sustainability pathways). The extent to which actors can successfully reposition themselves will depend on, for example, internal societal dynamics (S1: Social structure). The indicators for forces P1: Leadership in hydrogen technology and T2: Access to key hydrogen technologies provide a framework to help monitor what the four different scenarios outlined in Chapter 6 could mean in terms of hydrogen developments in the ARRRA region.

Force	Indicator	Monitoring
P2: Degree of global cohesion	Strength and stability of diplomatic relationships between major global players	Narratives concerning important diplomatic visits and interactions with leaders at international meetings and conferences Outcomes of diplomatic visits: such as, trade deals negotiated, shared intentions to address mutual problems, resolving disputes # of formal conflicts between nation states
	Extent to which major global powers strive towards and implement measures for digital sovereignty, possibly resulting in a 'fragmentation of the internet'	The emergence of national or regional plans for digital sovereignty – such as the idea of a regional, European cloud – which would prevent citizen's data being shared or circulated outside the country's or region's territorial borders Adoption of laws and regulations that 'close the borders' of the internet: i.e., aimed at blocking content from other countries as well as keeping content produced within the country inside
	Changes to military spending in relevant countries	Increases or decreases in national spending on military or defence activities. In particular, spending on high-tech defence technologies such as drones, hypersonic missiles and cyberwarfare, and the critical human capabilities for using these technologies in wartime
P3: Rule setters in global markets	Changes in economic, cultural, military and political power of the five 'world leaders' (United States, China, European Union, India and Russia)	Changes in economic power could be monitored by: • A region or country's GDP and annual growth rate • # of countries for which the country or region is the primary trade partner • Total amount of Foreign Direct Investments in other countries • Ability to wage economic wars Changes in cultural power could be monitored by: • Popularity of the country's or region's films and movies • Popularity of the country or region as a holiday destination • # of people who speak the country's language as a first or second language Changes in military power could be monitored by: • Relative military and defence expenditure • # of armed forces and sophistication of its organisation • Having or developing (nuclear) weapons • Having or developing mature cybersecurity-capabilities Changes in political power could be monitored by: • Whether a country has permanent position in the UN Security Council • Its (acknowledged) international leadership on climate change mitigation and global poverty eradication • Number of strategic alliances and memberships of cross-country organisations • Number of countries that follow a country lead in imposing trade bans and sanctions, for example for human rights violations
	Increasing competition from state-owned, state-controlled or state-influenced companies in free market economies	% of market capitalisation of foreign state-owned, state-controlled and state-influenced companies in free market economies # of the world's 100 largest multinationals that are state-owned, state-controlled or state-influenced Growth rates of state-owned, state-controlled or state-influenced companies in emerging and established markets Relative share of critical-materials supply chains controlled by state-owned, state-controlled or state-influenced companies Relative share of hydrogen supply chains towards the ARRRA region controlled by state-owned, state-controlled or state-influenced companies

Force	Indicator	Monitoring
EC3: Extent of globalisation	Extent to which relevant countries develop strategic industry policies with a focus on increased protection or nationalisation of critical industries	Published strategic policies for critical technologies, processes and materials Announcements of new trade bans, import tariffs or other instruments that create trade barriers for foreign parties on the domestic market
	Changes in regional trade growth rates	Increases or decreases in regional trade, as measured and regularly shared in OECD/WTO statistical data
	Changes to Global Foreign Direct Investment flows	Increases or decreases in invested amounts abroad, or changes in the types of countries in which investments are made, as measured and regularly shared by the OECD (Foreign direct investment in figures)
P4: Energy security	Energy dependency	The relative dependence of the ARRRA region on imported energy and the region's ability to meet its own energy needs, as measured by the ratio between net imports and gross available energy in the ARRRA region
	Energy supply diversity	The relative share of different energy sources in the total energy mix, as measured by the shares of petroleum, natural gas, coal, renewable electricity, hydrogen, biomass and nuclear in the total energy mix The relative reliance of the ARRRA region on particular suppliers Measured by: total number of energy suppliers to the ARRRA region and supply concentration (# of energy suppliers contributing to 50% of ARRRA's total energy imports)
	Electricity generation redundancy	Relative availability of backup electricity generation capacity, measured by the ratio of total generation capacity in relation to generation capacity required to meet total energy demand
	Extent to which European (strategic) energy reserves are filled and at what prices	'90% full' target per 1 October of each year
ENV2: Scarcity of raw materials	The evolution of global production amounts of essential transition metals and minerals	Changes in the total worldwide production of essential transition metals and minerals, such as copper, lithium, platinum, cobalt and bauxite (for aluminium) Data for five-year time periods made available annually by the British Geological Survey in its World Mineral Production reports
	Exploration budgets of major mining companies	Aggregate annual global exploration budget of some major mining companies (Glencore, BHP, Rio Tinto, Jianxi Copper, Vale, Zijin mining group)
	Exploration for raw materials within Europe	# of exploration projects filed within Europe Changes to exploration budgets for critical transition materials on European soil. This data is tracked in the European Commission's Raw Materials Information System (RIMS) / Raw Materials scoreboard
	Relative critical raw materials (CRM) import dependency	Reliance on particular suppliers, to be measured by • total # of CRM suppliers • # of CRM suppliers contributing to 50% of the ARRRA region's supply • % of supply coming from within the EU
S1: Social structure	Political preferences for individualisation or collectivisation of risks and uncertainties in life	Relative share of government expenditures on incapacity and other social benefits
	Public willingness to make individual behaviour changes for collective causes such as climate change mitigation	Average willingness of ARRRA citizens to change individual behaviour for climate change mitigation

Force	Indicator	Monitoring
ENV4: Sustainability pathways	Performance against REPowerEU targets, including: € Upscaling and accelerating hydrogen € Accelerated roll out of solar, wind and heat pumps € Easing permit/planning procedures	# of projects for hydrogen production, infrastructure (hydrogen pipelines and refuelling stations), storage and conversion for which construction has commenced (annually) Available funding (in millions of €), including amounts in calls from the 'Clean Hydrogen Joint Undertaking' and the 'Connecting Europe Facility' Adoption rates of solar PV and heat pumps in the built environment (annually) # of large-scale solar PV and wind projects for which construction has commenced (annually) Increasing or decreasing process time in permit/planning procedures in the ARRRA region
	Size and performance of ESG/green/ climate funds	Net new assets into ESG/Green/Climate funds per year Return rates of major ESG/Green/ Climate funds in comparison to the STOXX Europe 600 and S&P500 indices
	Share of investments annually (made or planned) in renewable energy solutions by large oil and gas companies	% of total annual investments (made or planned) in renewable energy solutions by major oil and gas companies
P2: Leadership in hydrogen (technology) development	National spending on innovation, demonstration and upscaling of hydrogen technologies	€of public funding annually available for innovation, demonstration and upscaling of hydrogen technologies
	Patents in hydrogen technologies	Total number of hydrogen-tech related patents in a nations' patent portfolio Relative number of triadic patents filed (# of patents filed in the EU, US and China for the same invention) in relation to total number of patents Quality assessment of patents for hydrogen-tech patents in a nations' patent portfolio (for example, for radicalness or novelty, which would be measurable with fewer links &references to previous patents and technologies, or technical relevance)
	The extent to which the hydrogen contributions of a nation's science institutes, think tanks and advisory bodies are considered 'high impact' in the global hydrogen field	# of references and citations to key published reports National share of top 10% most-cited scientific publications within energy related fields
	Leadership in hydrogen pricing	Emergence of hydrogen pricing hubs. Where will the marker price for hydrogen be set, and what (and whose) trade platforms will become used for hydrogen transactions?
T2: Access to key hydrogen technologies	Developments in affordability of critical hydrogen technologies	Evolution in investment amounts required for the development of one gigawatt electrolyser capacity. Market prices of commercially viable hydrogen technologies such as megawatt electrolysers and fuel cells
	Success of technology upscaling	Technology Readiness Levels of gigawatt-scale electrolysers
	Short-term availability of efficient carbon capture, utilisation or storage (CCUS) technologies	Technology Readiness levels of carbon sequestration at close to 100% capture rate Process time in permit/planning procedures, including potential delays to planned CCUS projects

TABLE 10 EXTENDED LIST OF EARLY INDICATORS

drift for transition

Erasmus Commodity & Trade Centre

TU Delft

CIEP