

Back from the Future

The Petrochemical industry in the Rhine-Scheldt Delta in 2030



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Chemagine 2030

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Summary

This report describes our vision for the petrochemical industry in the Rhine-Scheldt Delta in 2030. The petrochemical industry manufactures its products from artificial synthesis gas that consists out of carbon dioxide and hydrogen. Hydrogen is produced from the thermal cracking of water at temperatures higher than 900°C. These high temperatures are reached by using nuclear power. The carbon dioxide is extracted from the air by leading the air through adsorption units and concentrating the adsorbed carbon dioxide. With this synthesis gas methanol, ethylene, propylene, and even larger hydrocarbons can be produced without using oil. This new process route is a feasible technique based on existing technologies.

The foremost and most significant advantage of this vision is the preservation of the current infrastructure. The naphtha crackers making up the front side of the industry are replaced, whereas the back side is preserved; producing the same products and addressing the same market. The main benefits from this vision are that the majority of the processes within the production process is maintained, no employee layoffs are involved and investments made in the past do not become redundant.

An additional advantage of this vision is the competitive position of the Rhine-Scheldt Delta. By focusing on bulk production for the European market, the Rhine-Scheldt Delta's only competitors are other European companies. In Europe, the Rhine-Scheldt Delta offers several competitive advantages. There are two large ports (Antwerp and Rotterdam) in close proximity and a good railway infrastructure (HSL, Betuweline). Therefore industry in this region has a good competitive position.

To accomplish this vision in 2030, additional and highly detailed research and development of the proposed technologies are needed. Although the technology used for the production of synthesis gas already exists, the technology needs to be refined for large scale use. Great steps have been made in reducing the amount of nuclear waste produced by a nuclear power plant. Unfortunately, a solution to the waste problem is currently unavailable. It is essential to the preservation of the earth's environment that a solution is found. The industry needs to invest in research and build the new hydrogen and carbon dioxide production facilities so as to enable the industry to switch to the new production method as soon as it becomes profitable. The government needs to create more public support for nuclear energy. Furthermore, the government needs to provide financial support for the construction of the hydrogen and carbon dioxide production facilities.

The solutions proposed in this report are as revolutionary as they are simple. It provides a feasible and sustainable alternative to the world's ever increasing dependency on an energy source which is rapidly declining. This vision creates new ideals for a society facing serious challenges and makes the future shine brightly before us!

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Prologue

In today's fast changing business environment, the strategic decisions made today are of significant influence on a business's future. Scenarios are a useful tool to improve these strategic decisions. Scenarios are not projections, predictions or preferences, but alternative futures. Their purpose is to be challenging; think the unthinkable!

This report describes our vision for the petrochemical industry in the Rhine-Scheldt Delta in 2030. The conditions with which our scenario needs to comply are given in the first chapter where we describe the main stakeholders in the petrochemical industry in the Delta and their interests. In the second chapter we identify two significant events which lead to our vision for 2030. In the third chapter we discuss the process and its technical aspects of our vision and in the fourth chapter we evaluate our vision on scale, costs, and stakeholder satisfaction. In the fifth chapter we give a number of recommendations to make our vision a reality in 2030.

Finally, we want to emphasize that scenarios are based on intuition. They are not predictions of the future, nor are they a contentious view of the future. They may describe a framework and how this framework changes under qualitative and quantitative aspects. However, ideas are not excluded on the basis that they cannot be measured or are not fully developed at this point in time. Our vision for 2030 incorporates several uncertainties and is only one of the many possibilities available to the petrochemical industry. We are however convinced that with the technical advances expected in the future our vision is very well achievable in 2030.

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Chapter 1 Scenario Basis

This chapter provides the basis for the development of our scenario and vision. Our vision for the industry in 2030 depends on two aspects, namely the concerns of the stakeholders in the petrochemical industry and significant events which have affected the development of the petrochemical industry in the past and will continue to do so in the future. The influence of these concerns and events on our vision for 2030 is shown schematically in Figure 1.

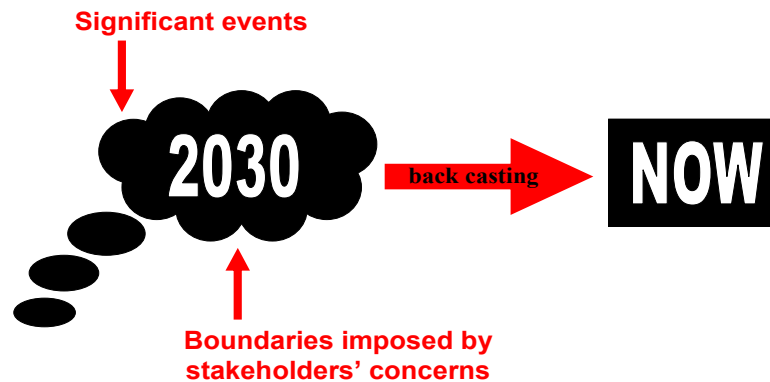


Figure 1: scenario basis

1.1 Scenario conditions

With our scenario, we aim to achieve the highest satisfaction for all stakeholders in the petrochemical industry in the Rhine-Scheldt Delta. The main stakeholders are the petrochemical companies themselves, the government, the inhabitants surrounding the petrochemical companies, and environmental organizations.

Petrochemical companies

The petrochemical companies operating in the Rhine-Scheldt Delta are committed to this region through their current facilities. Their main concern is to be competitive and profitable. Additionally, the petrochemical companies aim to comply with safety and environmental legislation imposed by the local government and the European Union.

Government

The Dutch and Belgian government's main interests are to stimulate the nation's economy and meet the safety and environmental legislation imposed by the European Union and global agreements such as the Kyoto Protocol signed in 1997. Economy related interests are preserving jobs and increasing export. Furthermore, it is of interest to the government to attain a high level of autonomy so as not to be dependent of other (possibly politically unstable) countries for their energy supply.

Inhabitants

One of the main concerns of people living in close proximity to petrochemical facilities is a safe and non-polluted (living) environment. Additionally, high employment levels are very important to the inhabitants.

Environmental organizations

The main concern of environmental organizations is that the petrochemical industry employs its activities in a sustainable manner.

1.2 Significant events

Two significant events influence the development of the petrochemical industry in the Rhine-Scheldt Delta, namely the decrease in global oil reserves and an increase in competition from foreign countries.

Decreasing oil reserves

Estimations of the global oil reserves and consumption^[1] predict that the available oil reserves are only sufficient for the next 50 years. Oil is not only a source of energy for the petrochemical industry, but also one of the most important raw materials used by the industry to produce many goods ranging from packaging material to televisions. In the event that oil becomes scarce, the petrochemical industry needs to make use of another source of energy and raw material.

Increasing global competition

With the increasing globalization of today's business environment, companies experience fierce competition with different competitors in each outlet market. Therefore, by choosing a specific outlet market, a company can 'choose' its competitors. Also, the focus of the petrochemical industry (i.e. bulk or specialization) influences who the industry's main competitors are.

1.3 Scenario choices

Our vision for 2030 has to be one in which oil is no longer used and the industry is competitive. The vision has to lead to the preservation or even the creation of employment, has to be safe, sustainable and provide a certain level of autonomy to the region. Keeping these aspects in mind, the future of the petrochemical industry depends on the following choices:

1. What will the industry focus be?
2. What will the outlet market be?
3. Which raw material source will be used?
4. Which energy source will be used?

Chapter 2 Scenario development

This chapter shortly describes the choices for the industry focus, the outlet market and the raw material source as mentioned in the previous chapter. The fourth choice which influences our vision, the energy source, will not be discussed in this chapter. This choice will only be discussed once we decide which raw material, industry focus and outlet market to use.

2.1 Industry focus

The demand for bulk products such as propylene is high and will keep increasing in the future.^[2] Bulk production is characterized by high-volume production, low-added value and simple products. The production process is divergent; a small number of raw materials leads to a basic product with many possible applications. The majority of the companies in the Rhine-Scheldt Delta already focuses on bulk production. These companies must attain bulk production as their core business. By doing so the current infrastructure can be preserved, which also means the preservation of current employment. Therefore, we believe the industry should focus on bulk production in 2030.

2.2 Outlet Market

The choice for an outlet market directly influences sales volumes. If the outlet market is small, a high market share needs to be obtained to gain sufficient sales. However, if the outlet market is large, a smaller market share may lead to sufficient sales. The choice for an outlet market also depends on the industry focus. The industry focus defines the level of added value of the products and therefore the amount of transportation costs that are justified in order to sell the product. With the choice for bulk production as industry focus, the industry has to choose for the European outlet market. Due to the growing demand for propylene and plastics, the European market has a potential for high sales. By choosing bulk production as industry focus and Europe as outlet market, the competition from low-cost countries is eliminated. The costs for shipping propylene between the ports of Antwerp and Shanghai are 0.45 US\$/kg.^[3] Since the average labour costs per kilogram of propylene produced in the Rhine-Scheldt Delta is only 0.01 US\$ (see Appendix I), the costs to ship the propylene to Europe are significantly higher than the labour costs. Even if the labour costs in the low-cost countries are considered negligible, the transportation costs still exceed the labour costs to a large extent. From this we conclude that the only competitors on the European market will be other European companies.

Although competition from low-cost countries is prevented by focusing on bulk production, these countries can exert influence on the industry by taking over companies, i.e. inward investments. The main concern of opponents of inward investments is that foreign companies obtain influence in the local region/market. Supporters of inward investments argue that the situation of inward investments must be compared to the situation in which there is no investment at all, and not to the situation in which the investment is made by companies from the local region/market. Therefore the supporters see several opportunities for the industry; a boost of the productive capacity, the import of new technology and management practices, and the reduction of interest rates. These advantages compensate for the relatively low loss of influence on a managerial level. Researches on the effects of inward investments in the Netherlands^[4], Belgium^[5] and the

United States^{[6],[7]} show that there is no reason to protect companies from foreign takeovers. This conclusion is supported by the Dutch government who stimulates inward investments in Dutch industries.^[4]

2.3 Raw Material

Due to the rapid decrease in the global oil reserves, the (petro-) chemical industry has to seek other raw materials. The best alternative is the use of synthesis gas which is a mixture of hydrogen and a carbon source. Synthesis gas can be produced out of several different sources and can be further processed to hydrocarbons. Currently, synthesis gas is produced by converting fossil fuels into hydrocarbons. Many experimental installations are built and even production plants emerge all over the world which use fossil fuel based synthesis gas as their raw material.^[8] The ever decreasing oil reserves necessitate the petrochemical industry to develop a new way to produce synthesis gas. This artificial synthesis gas consists of hydrogen and a carbon source and can be processed in a similar way as synthesis gas from fossil fuels.

2.4 Conclusion

Our vision is based on the manufacturing of bulk products for the European market using synthesis gas as raw material. The industry in the Rhine-Scheldt Delta will continue to supply a significant part of the European market and the jobs in the industry will be preserved. The next challenge is to find a hydrogen and carbon source to produce synthesis gas. This will be discussed in the following chapter.

Chapter 3 Scenario Description

The synthesis gas used in current chemical processes is a mixture of carbon monoxide and hydrogen. Our vision is based on the use of artificial synthesis gas which is produced from two substances, namely water and carbon dioxide that is extracted from the air. The water is converted into hydrogen and together with concentrated carbon dioxide it forms our synthesis gas. From this synthesis gas hydrocarbons can be produced. The hypothesis that hydrocarbons can be produced out of water and carbon dioxide may seem opportunistic, but in this chapter its feasibility based on existing technologies will be proven. The first section provides a general process description and the second section provides the technical aspects of the process in more detail. In this description we take the propylene production of 500 ktons per year, which equals the production of a current naphtha cracker. Chapter four evaluates the scale of the total process in more detail.

3.1 Process description

The production of hydrocarbons out of water and carbon dioxide from the air consists of three processes; the production of hydrogen, the extraction of carbon dioxide from the air in a concentrated form, and the production of hydrocarbons from the carbon dioxide and hydrogen. There are several options to produce hydrogen, for example electrolysis with solar or wind energy. Also, carbon dioxide can be easily extracted from the exhaust from fossil plants. However, this scenario is based on the most extreme vision and therefore is independent of climate, weather conditions or fossil fuels.

Our vision for the production of hydrogen is based on the thermal cracking of water at high temperatures ($>900^{\circ}\text{C}$). Dr. ir. J.L. Kloosterman^[9] conducts research on catalytic thermo cracking processes, in which nuclear heat is used to split water into hydrogen and oxygen. Nuclear energy is an efficient process to obtain high temperatures without the use of fossil fuels. Thermal cracking is a highly efficient ($\sim 50\%$) catalytic process in its own right. By combining the thermal cracking of water into hydrogen and oxygen with the electricity generating capabilities of a nuclear (power) plant, an extremely efficient process is created.^[9] The technical details for the nuclear production of hydrogen will be described in more detail in the following section.

Carbon dioxide needs to be available in a concentrated form. In order to design a sustainable process, carbon dioxide is extracted and concentrated from the air. There are several reasons to use carbon dioxide from the air, namely

- carbon dioxide is available in the air on a large scale;
- a closed carbon dioxide cycle is created, i.e no production of extra greenhouse gasses;
- climate change concerns may warrant carbon dioxide reductions rather than only carbon dioxide emission reductions.

Current research by F.S. Zeman^[10] and K.S. Lackner^[11] shows that extraction of carbon dioxide from the air is possible and that carbon dioxide can be concentrated by leading air through adsorption units. The thus obtained carbon dioxide can then be used in further processing steps. In the next section these adsorption units are also described in more detail.

The final step is the production of hydrocarbons out of the concentrated carbon dioxide and the formed hydrogen. Carbon dioxide and hydrogen cannot be transferred into alkenes and other hydrocarbons directly. The carbon dioxide and the hydrogen are first converted to methanol. This conversion is a well known, catalytic chemical reaction, which is carried out on large scale and with high efficiencies.^[12] A number of chemical processes are known in which methanol is used. The synthesized methanol can either be used in these kinds of processes or can be converted into alkenes. This last step, the conversion of methanol into alkenes such as propylene, is also a well known chemical transformation.^[13] A schematic overview of the suggested total process is shown in Figure 2.

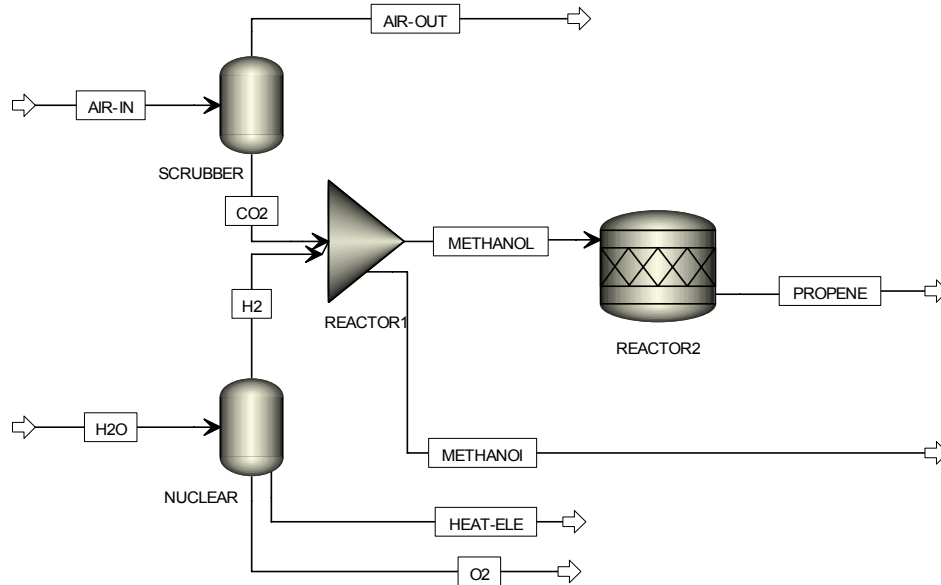
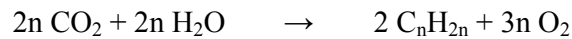


Figure 2: schematic overview of the total process

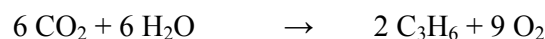
The overall reaction for the hydrocarbon production out of hydrogen from water and carbon dioxide from air becomes



The overall process is very clean and highly sustainable. Only carbon dioxide and water are used to produce hydrocarbons and no pollutants are produced. The process also contributes to a total carbon dioxide and water cycle since both materials are reformed when the product is combusted. The oxygen produced in the thermo cracking process might be used in other process steps (e.g. combustion processes) instead of being emitted to the air.

3.2 Technical description

For the sake of simplicity we assume that the alkene produced in our plant is propylene. The steps in the propylene formation process are the production of hydrogen from the thermal cracking of water, the extraction of carbon dioxide from the air and the formation of propylene from the produced hydrogen and carbon dioxide. The overall reaction of the propylene production is shown below.



Hydrogen production in nuclear (power) plant

Recent developments have led to a new generation of reactors that no longer contain nuclear fuel rods, but use small coated particles of uranium with a diameter of 0.5mm. Around 15,000 of these coated particles are embedded in one graphite sphere with a diameter of 60mm.^[9] Approximately half a million of these spheres form a so called pebble bed reactor. These reactors are easier to control than the old generation reactors operational today. The new generation of reactors also eliminate the risk of a nuclear disaster. In the event that the cooling mechanism should fail completely, the reactor will not reach critical temperatures and a nuclear meltdown does not occur. This means that these new generation reactors are inherently safe.

The largest problem with nuclear power is nuclear waste. Nuclear waste is radioactive for a very long time, ranging from 250 up to 5000 years. New methods are being developed to increase the percentage of nuclear waste that can be recycled and research shows that 97% of all the nuclear waste can be reused.^[9] This implies a considerable decrease in the amount of nuclear waste. Additionally, reusing the nuclear waste decreases the overall uranium usage by the reactors. The new generation reactors' uranium consumption is so low that sufficient levels of uranium will be available for the next 50,000 years.^[9]

These new generation reactors are used for the thermal cracking of water at high temperatures (900°C). In this catalytic thermo cracking process, nuclear heat is used to split water into hydrogen and oxygen. Water enters the reactor and reacts with I₂, SO₂ and another H₂O molecule to form H₂SO₄ and HI. At high temperatures HI splits up to form H₂ and I₂, and H₂SO₄ splits up to form O₂, SO₂ and H₂O. Below the reaction steps are written explicitly and in Figure 3 a schematic view of the process is shown.

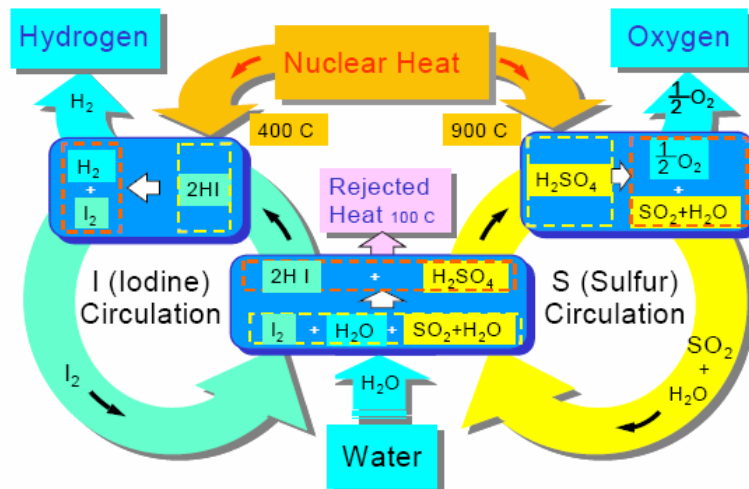
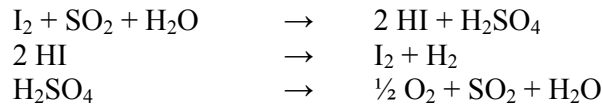


Figure 3: schematic overview thermal cracking of water^[9]

The efficiency of the process is defined as the ratio of the amount of heat that is used versus the energy equivalent of the amount of hydrogen that is produced. At 20°C, hydrogen has an energy equivalent of 10⁷ kJ per cubic meter. The efficiency of converting water into hydrogen and oxygen strongly depends on the decomposition temperature and is

52% at 950°C. The remaining 48% is used for electricity production and as a heat source for other processes which makes the overall process efficiency more than 70%. This is considerably higher than the efficiency in a conventional fossil fuel power plant, which is 35%. At this temperature, a 1200 MW nuclear plant can produce more than 250 ktons of hydrogen per year, which is sufficient for a propylene production of 535 ktons per year.^[14]

Carbon dioxide concentration

The carbon dioxide concentration in the air is only 370ppm^[10] and in order to obtain enough carbon dioxide required for the production of 500 ktons of propylene per year, the dimensions of the adsorption equipment to extract the carbon dioxide from the air have to be considerable. However, the investment costs are reasonably low at only 10 million US\$.^[11] An example of a feasible device to generate the required airflow is shown in Figure 4.

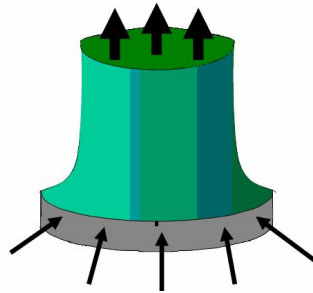


Figure 4: carbon dioxide extraction tower

The generated air flow is led through a trickle bed in which the carbon dioxide is effectively adsorbed. The process starts with air containing 370ppm of carbon dioxide and finishes with pressurized carbon dioxide and clean, carbon dioxide poor air. The capture process is achieved by the formation of sodium carbonate from sodium hydroxide and carbon dioxide from the air. This is followed by the recovery of the sodium hydroxide using calcium hydroxide where the calcium hydroxide is converted into calcium carbonate. The calcium hydroxide is recovered by calcinating the limestone precipitate and subsequent slaking with water.^[10] The individual reactions are listed below.

Figure 5 shows a schematic overview of the process:

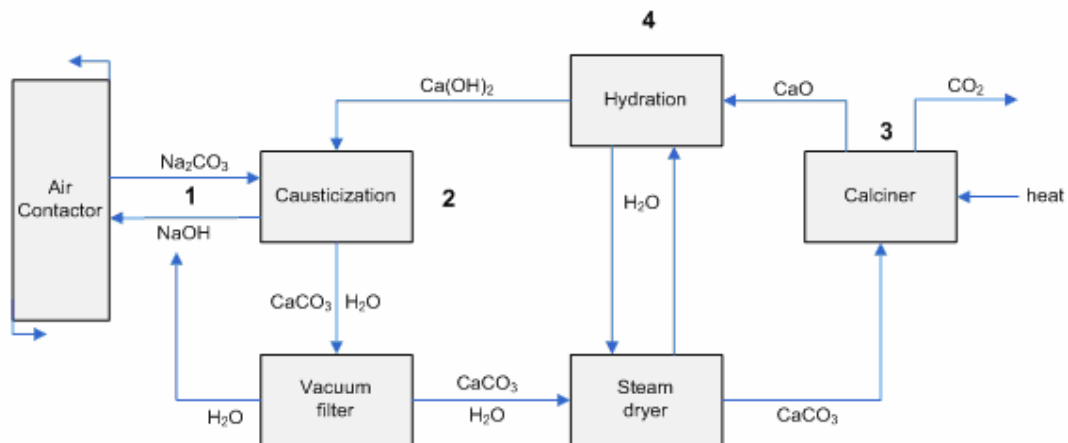
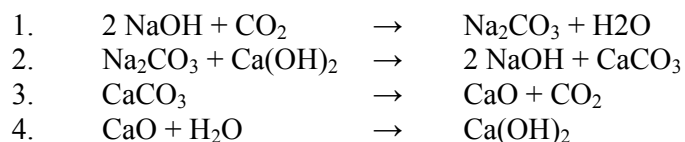


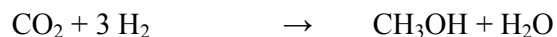
Figure 5: schematic overview of carbon dioxide extraction and concentration



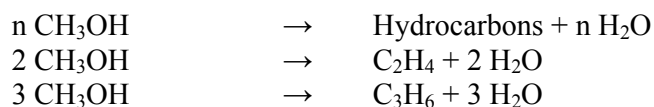
In summary, the system uses sodium hydroxide as a sorbent. An aqueous solution drips in the trickle bed and thus allows the capture of carbon dioxide from the air that passes through the system. When the sorbent solution has reached the bottom of the system, it is either re-circulated or removed from the system for recycling. The purpose of the desorbing unit is to strip the carbon dioxide from the spent sorbent and return fresh sorbent to the capture device. After the carbon dioxide has been stripped, it is compressed and transferred to the next process step. Research shows that the majority of the cost and energy demands occur in the recycling of the calcium carbonate.^[10] This energy comes from the nuclear plant. The cost of mixing the solutions and filtering out the precipitate is assumed to be low. The primary chemical reaction in this process is the thermal decomposition of calcium carbonate to concentrated carbon dioxide and carbon monoxide.^[10]

Propylene formation

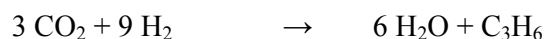
The pressurized carbon dioxide from the extraction unit reacts with the hydrogen from the nuclear plant in order to form methanol as an intermediate and propylene as a basis for further petrochemical reactions. For the hydrogenation of carbon dioxide a good catalyst is lead-impregnated Cu-ZnO(Al_2O_3) which achieves a 98% efficiency in converting carbon dioxide to methanol.^[12] This reaction is shown below:



In the next process step the produced methanol reacts further to form propylene. The use of manganese-doped aluminosilicates as a catalyst results in a selective (60%) and efficient (90%) production of ethylene and propylene from a methanol-water mixture.^[13] This reaction is shown below:



The overall reaction for the formation of propylene from carbon dioxide and hydrogen can now be written explicitly:



3.3 Conclusion

We have shown that the formation of hydrocarbons out of carbon dioxide from the air and hydrogen from water is feasible with readily available technology. Future developments will improve these technologies further and make the process even more efficient.

Chapter 4 Evaluation

The production route described in the previous chapters is a perfect solution for the production of propylene without using oil. This production can only be justified if current production scales can be maintained and the costs involved are not significantly higher than the costs encountered when using oil as a raw material for propylene production.

The first section describes the scale necessary for the total Dutch and Belgian petrochemical industry. The second section discusses the costs of producing propylene out of carbon dioxide from air and water. In the third section the benefits of our vision are discussed. Finally, we discuss some points of attention.

4.1 Scale

To produce 500 ktons of propylene per year, a nuclear plant equivalent to a 1200 MW power plant is sufficient as it produces 264 ktons of hydrogen per year out of which 535 ktons of propylene can be produced. The required amount of carbon dioxide to produce this amount of propylene is 1,839 ktons per year, which is equal to 5 ktons per day. The concentration of carbon dioxide in the air is 370ppm and the efficiency of the adsorption process is assumed to be 50%. Therefore, in order to obtain sufficient levels of carbon dioxide, an airflow of 14 km³ per day, which contains approximately 10 ktons of carbon dioxide, has to be achieved. In the device shown in Figure 4 the incoming air is heated with the residual heat from the nuclear reactor. This causes an updraft inside the tower which has an opening of 10,000 m². Heating the air causes an updraft in the excess of 15 m/s which generates an airflow of ~15 km³ per day through the tower. This is even higher than the minimum amount required for the production of 5 ktons of propylene per day. For more information on these calculations see Appendix II.

4.2 Costs

The equipment described in the previous chapter produces 535 ktons of propylene per year, which is in the same order of magnitude as a current naphtha cracker. This production rate is the basis for the cost calculations in this section.

A rule of thumb for the cost price of chemical bulk products is that the raw material costs are 80% of the cost price. We will compare the raw material costs for the propylene produced from oil with the raw material costs for producing propylene from artificial synthesis gas comprising of hydrogen and carbon dioxide.

The raw material costs involved in the producing of propylene from artificial synthesis gas consist of the following aspects. For more details see the Appendix III:

- *Costs of producing hydrogen*
Hydrogen produced in a 1200 MW nuclear plant at 950°C costs **0.70 US\$/kg** of propylene.
- *Costs of carbon dioxide*
The costs of carbon dioxide consist of two aspects. Firstly the costs involved in the scrubber itself and secondly the costs encountered in concentrating the carbon dioxide from the scrubber. The costs of the scrubber are **0.002 US\$/kg** of propylene and the costs of the extraction of the carbon dioxide are **0.23 US\$/kg** of propylene.

The overall raw material costs of producing one kilogram of propylene from artificial synthesis gas are:

$$(0.70 + 0.002 + 0.23) = \mathbf{0.93 \text{ US\$/kg}}$$

Since the current cost price for propylene produced from oil is 1 US\$/kg, the raw material costs are 0.8 US\$/kg. These raw material costs are directly dependant on the oil price. We expect the oil price to increase dramatically in the coming years due to high demand and low availability of oil on the global market.^[1] At the moment the oil price is 66 US\$ per barrel. A breakeven point is reached when the oil price reaches:

$$\frac{0.93}{0.8} \times 66 = \mathbf{76.73 \text{ US\$ per barrel}}$$

There are three factors that influence this breakeven point:

- Sales of by-products
By using nuclear power plants for the thermal cracking of water, not only hydrogen is produced, but also electricity, heat and pure oxygen. These by-products can be sold.
- Carbon dioxide emission
By using nuclear power plants, carbon dioxide is no longer emitted to the air by the industry. Also, carbon dioxide is extracted from the air to use as a raw material. Therefore the industry will no longer face carbon dioxide emission costs.
- Decreasing costs
The investment costs of the used technologies will decrease in time. Also after research technologies will become more efficient and therefore the operational costs will decrease in time as well.

If these factors are taken into account, we expect the breakeven point to decrease to **45 US\$ per barrel**. If we compare this to the current oil price, we see that this scenario is a feasible option.

4.3 Benefits

We have shown our vision for the petrochemical industry in 2030 to be feasible. This section reviews the important benefits flowing from our vision.

Continuity

An important advantage of our vision is the preservation of the current infrastructure of the petrochemical industry. The front side of the industry (the naphtha cracker) changes, but the back side is preserved because the same products are produced and the same outlet market is addressed. This means that the majority of the processes within the industry are maintained. Also, no employee layoffs are involved and investments made in the past are not redundant. In addition to maintaining the infrastructure of the petrochemical industry, the infrastructures of secondary industries are also maintained. Customers of the petrochemical industry are still supplied with the same products and are therefore able to continue with their own production processes.

Competitive position

By focusing on bulk production for the European market, the industry's only competitors are other European companies. In Europe, the Rhine-Scheldt Delta offers several competitive advantages. There are two large shipping ports (Antwerp and Rotterdam) in close proximity and a good quality railway infrastructure (HSL, Betuweline). The industry therefore has an excellent competitive position.

Sustainability

An extremely positive effect resulting from the use of nuclear energy is the elimination of carbon dioxide emission in the energy supply chain. The carbon dioxide emission in the energy supply chain is one of the major contributors to the total level of carbon dioxide emission. If nuclear power would be used for 75% of the total energy supply worldwide, carbon dioxide emission would decrease with 20%.^[15] A recent investigation shows the cost effectiveness of carbon dioxide reduction by means of a number of techniques. This cost effectiveness indicates the costs in euros for the reduction of one ton of carbon dioxide emission. Out of several available options, nuclear energy is the most cost effective at 8€/ton of carbon dioxide compared to wind energy at 59€/ton and bio fuels for transportation at 194€/ton!^[16] The remaining carbon dioxide in the air is extracted from the air by the carbon dioxide scrubbers and used for the production of hydrocarbon. The combination of nuclear energy and carbon dioxide to produce hydrocarbons is therefore a clean and sustainable solution.

Safety

The nuclear (power) plants we propose in our vision use new generation nuclear reactors. These new generation reactors are inherently safe and the treat of a nuclear meltdown is nonexistent. As a nuclear meltdown is no longer possible, the new generation nuclear reactors are a less attractive target for terrorist attacks. The impact of an attack on a new generation nuclear power plant would be the same as the impact on a conventional coal or gas powered power plant.

These benefits show that our vision leads to high satisfaction for the main stakeholders mentioned in chapter two. The industry can continue to produce and compete in the current market, the industry preserves its competitive position, employment in the region does not decrease, and production is safe and partly sustainable. Unfortunately, our vision has some points of attention which will be discussed in the following section.

4.4 Points of attention

The two major problems with the use of nuclear energy are the nuclear waste and the social acceptance of nuclear power.

Nuclear Waste

An issue concerning all nuclear power plants and which needs to be addressed is the waste problem. As mentioned previously, new techniques make it possible to reprocess spent nuclear fuel.^[9] This means that only three percent of the used nuclear fuel is actual waste. Combining this with the new generation nuclear reactors, the amount of nuclear waste produced every year can decrease dramatically. Nevertheless, more research is needed to change this small amount of waste into harmless or useful materials.

Social Acceptance

Although the new generation nuclear reactors are inherently safe, many people are still afraid and uncertain about nuclear energy after disasters such as that which occurred in

Tsjernobyl in the Ukraine in 1986. Today, even if people are convinced of the need for nuclear reactors, most people still do not want to live near a nuclear reactor (not in my backyard!). However, we predict that in the future this resistance against nuclear energy will decrease. Awareness of the new and safer reactors can be stimulated through information campaigns. A good example of this is the advertising campaign in France around 1990, which led to a wider acceptance of the use of nuclear energy. Additionally, increasing energy prices will stimulate development and acceptance of alternative energy sources.

Chapter 5 Back casting

In this chapter we discuss the path from our vision on 2030 back to the present. The three parties involved are the industry, the scientific community, and the government. In Figure 6 an overview of the overall cooperative structure that needs to be followed by the three parties to reach our vision for 2030 is given. The figure shows the interaction which needs to be achieved between the parties in order to produce and improve the designs for the production of hydrocarbons from hydrogen and carbon dioxide after each optimization cycle. By building the hydrogen and carbon dioxide plants one by one with several feedback loops, the opportunity arises to learn and improve the designs where necessary before building a new plant.

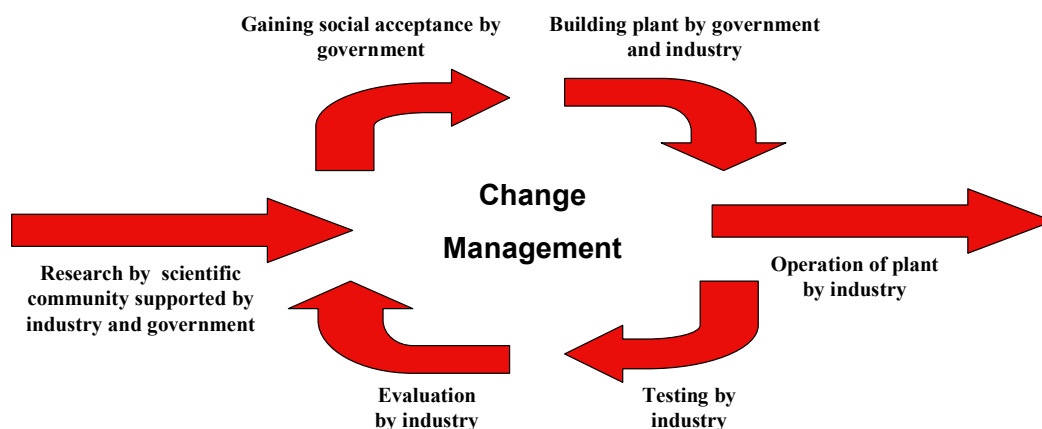


Figure 6: change management structure

In the following sections we provide recommendations for all of the parties involved in the design and building process. The last section gives an overview of the milestones that need to be reached during this design and building process.

5.1 Industry

By the year 2030 we expect the oil reserves to start decreasing and the oil price to reach at least the breakeven point of 45 US\$/barrel. Therefore it is advisable that the petrochemical industry has already made the transition from fossil fuel based hydrocarbon production to the production of hydrocarbons from water and carbon dioxide by 2030. This revolutionary turnaround will not be achieved in a few years; therefore a thorough plan is needed to accomplish this transfer. Replacing all naphtha crackers in the Rhine-Scheldt Delta would result in eight new nuclear plants being built. However, to ensure a smooth and gradual transition only five new nuclear power plants are desired by the year 2030.

The time required to build five nuclear plants is ten years. Additionally the production of hydrocarbons from water and carbon dioxide has to be fully operational in 2030. Therefore the building of the power plants should start in 2020. We propose to build a new nuclear plant every two years in order to create an optimal learning curve as described in Figure 6. These plants can be used for the production of electricity in the early years and will start the production of hydrogen as soon as it becomes profitable. Therefore in 2020 the technology and engineering knowledge incorporated in the production of hydrogen from water must be ready and large scale testing programs must be completed. This is only

feasible when the engineering phase starts in 2017. In order to meet the carbon dioxide emission regulations the building of carbon dioxide extraction units should already start in 2015. The concentrated carbon dioxide can be stored in the earth^[11] until the production of hydrocarbons commences. These installations do not necessarily have to be build near a propylene production site, because carbon dioxide is not a harmful gas and can be transported through pipelines. Nevertheless, time and money is saved if the carbon dioxide extraction units are in close proximity to the hydrocarbon production plant(s). Another advantage of building next to the nuclear plant is that the residual heat from the nuclear plant can be used in the extraction process. The engineering phase for the carbon dioxide extraction units starts in 2012. Additionally the industry should stimulate research and development on both technologies in order to be able to commission the engineering phase at the appropriate moment.

Schematic overview:

2006 – 2015	Stimulate research and development of relevant technologies
2012	Engineering phase for carbon dioxide extraction units starts
2015	Building of carbon dioxide extraction units starts
2017	Engineering phase for nuclear plants starts
2020	Building of nuclear plants starts
2030	Fully operational plant

5.2 Government

The government is concerned with preserving employment in the petrochemical industry, securing a stable economy, and ensuring that global environmental agreements are fulfilled. Therefore it is crucial that the government is involved in the development of the new production processes. After 2030 the government may choose to privatize the nuclear (power) plants.

To achieve a fully operational plant in 2030 the government partly participates in the building projects and supports these projects by means of subsidies in the period from 2020 up to 2030. The government needs to choose the location for the nuclear plants carefully, because the nuclear plants need to be close to the propylene production sites. This is due to the risks involved in transporting the hydrogen produced by the nuclear plants over long distances. From 2010 to 2020 the government needs to provide financial support for the development of the new process route. This can be done by financial injections or by creating partnerships with the involved industrial companies. In order to meet the carbon dioxide emission regulations the building of carbon dioxide extraction units should be stimulated and even enforced in the period from 2010 till 2020. The government should start a (media) campaign to promote the use of nuclear power to convince the public of the safety of the new generation reactors as soon as possible. This is crucial to the success of the new generation nuclear reactors. We believe that public resistance to nuclear power forms the main obstruction in the implementation of the production of hydrocarbons from water and carbon dioxide.

Schematic overview:

2006	Start (media) campaign to promote the use of nuclear power
2006 – 2020	Financial support for the development of the new process route
2010 – 2020	Stimulate building of carbon dioxide extraction units
2020 – 2030	Participate in the building projects and supports them by means of subsidies
2030	Start privatization of fully operational plants

5.3 Scientific community

The implementation of the newly developed technology should start no later than 2020. Therefore the theoretical background and the underlying fundamental understanding must be realized by 2017 for the nuclear power plants and by 2012 for the carbon dioxide extraction units. After 2020 the scientific community may choose to investigate other alternatives for the extraction of carbon dioxide such as nano-filtration units. In the time period from 2010 to 2017 the details of the nuclear plant should be further developed and, because the development of the carbon dioxide extraction units has priority in order to meet environmental regulations, in the years from now until 2012, the details of the carbon dioxide extraction unit have to be further developed. To finance these investigations the petrochemical industry and the government need to provide financial support to the scientific community. If the government stimulates the research sufficiently, the Dutch/Belgium region can become a leader in this technology.

An additional concern is nuclear waste. The scientific community needs to find a solution to this ever present concern. The nuclear waste volumes need to be reduced and solid solutions need to be found for the conversion to harmless materials or the storage of nuclear waste.

Schematic overview:

- 2006 – 2030 Investigate nuclear waste problem
- 2006 – 2012 Research and development on carbon dioxide extraction units
- 2010 – 2017 Research and development on nuclear power plants
- 2020 – 2030 Investigate other alternatives for the extraction of carbon dioxide

5.4 Overview

Figure 7 shows a Gantt chart with the activities and milestones all three parties have to execute in order to achieve the desired vision in 2030.

		2005	2010	2015	2020	2025	2030
Industry	H2		Invest in science for development	Testing plant	Build nuclear plants, link to chemical plants		
	CO2		Testing scrubber	Build first scrubbers, put CO2 in ground	Use CO2 for chemical plants		
Government			Campaign to promote nuclear energy				
			Participate in building CO2-scrubbers		Participate in building power plants		Privatizing
			Subsidy development new process route				
Scientific	H2		Develop and test H2-producing plants				
Community	CO2		Research and develop scrubber		Investigate alternatives for CO2-extraction		
	Nuclear waste		Investigate nuclear waste problem				

Figure 7: Gantt chart for all involved parties to 2030

This chapter illustrated the actions necessary for the three parties in order to achieve our vision for 2030 and the need for cooperation between these parties. With this figure we show that our vision is not only feasible from a technological perspective, but also achievable within the time available.

Epilogue

This report gives our vision on the petrochemical industry in the Rhine-Scheldt Delta in 2030. Our vision provides a solution to the problems that the industry will face in the future and meets the needs of the stakeholders. Although our vision is proven feasible, additional and highly detailed research and development of current techniques and technologies is needed.

The formation of our vision was preceded by a period of orientation. During this phase we consulted many experts from different fields. We would like to thank all these experts for their contribution, in particular

- Prof. ir. C. Daey Ouwens, for his expertise on alternative energy sources, in particular biomass;
- Dr. ir. J.L. Kloosterman, for his expertise and the provided literature on hydrogen producing nuclear plants;
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- Dr. ir. A.M.C. Lemmens, for his feedback on the social impact and the implications on our vision;
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- Dr. ir. G.P.J. Verbong, for his guidelines on forming a scenario;
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- Ir. E. Vinken, for her guidance as tutor.

We trust that this report will capture your imagination and enthusiasm regarding our vision for the petrochemical industry in the Rhine-Scheldt Delta in 2030.

Chemagine 2030
Chris Aldewereld
Bart Dautzenberg
Marte Guldemond
Johan Wijers

References

- [1] <http://www.trendlines.ca/economic.htm>
- [2] *Forecast of Global Supply and Demand Trends for Petrochemical Products*, Japanese Ministry of Economy, Trade and Industry, <http://www.meti.go.jp/english/information/downloadfiles/c0517PetroProe.pdf>
- [3] Provided by Unigas Rotterdam during telephone interview
- [4] <http://www.netherlands-embassy.org/article.asp?articleref=AR00001842EN>
- [5] *The performance of foreign and national take-overs in Belgium*, European Business Review, 1997
- [6] M. Wayne Marr Jr., Sanjeev Mohta & Michale F. Spivey, *An analysis of foreign take-overs in the United States*, Managerial and decision economics, vol. 14, no. 4, pp.285-294, 1993
- [7] Michael Ulan, *Should the U.S. restrict foreign investment?*, Annals of the merican academy of political and social science, vol. 516, pp. 117-125, 1991
- [8] Michael J Corke, GTL technologies focus on lowering costs, Oil & Gas Journal; Sep 21, 1998; 96, 38; ABI/INFORM Global, pg. 71
- [9] Dr. ir. J.L. Kloosterman, <http://wwwtest.iri.tudelft.nl/~klooster/research/h2.php>
- [10] Frank S. Zeman, An Investigation into the Feasibility of Capturing Carbon Dioxide directly from the Atmosphere, <http://www.americanenergyindependence.com/recycleco2.html>
- [11] K. S. Lackner, H.-J. Ziock, P. Grimes, Carbon Dioxide Extraction from Air: Is it an Option?, B. Sakkestad, Ed., Proceedings of the 24th International Conference on Coal Utilization & Fuel Systems, Clearwater, Florida (1999), and K. S. Lackner, P. Grimes, H.-J. Ziock, "Carbon Dioxide Extraction from Air?" LAUR-99-5113 (Los Alamos National Laboratory, 1999)
- [12] I. Melián-Cabrera, M. López Granados, P. Terreros, J.L.G. Fierro, *CO₂ hydrogenation over Pd-modified methanol synthesis catalysts*, Catalysis Today 45 (1998) 251-256
- [13] Friedrich August Wunder, Ernst Zngo Leupold, *A Selective Pathway from Methanol to Ethylene and Propene*, Angew. Chem. fnt. Ed. Engl. 19 (1980) No. 2, 126-127
- [14] K.R. Schultz, *Use of the Modular Helium Reactor for Hydrogen Production*, World Nuclear Association Annual Symposium, London, 3-5 September 2003
- [15] Dutch Ministry of Housing, Spatial Planning and the Environment, *The National Inventory Report 'Greenhouse Gas Emissions in the Netherlands 1990-2003'*, May 2005
- [16] B.W. Daniels (Energieonderzoek Centrum Nederland) & J.C.M. Farla (Milieu- en Natuurplanbureau), *Potentieelverkenning klimaatdoelstellingen en energiebesparing tot 2020: analyses met het Optiedocument energie en emissies 2010/2020*, February 2006

Appendix I Labour costs

We consider the following specifications for an average size naphtha cracker:

production capacity:	500 ktons per year
number of employees :	100
average labour costs:	50,000 US\$/employee/year

Labour costs per kg propylene produced:

$$\frac{100 * 50,000}{500 * 10^6} \equiv 0.01 \text{ US\$}$$

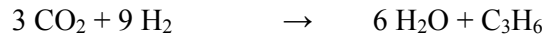
We assume that in the production of hydrocarbons from water and carbon dioxide the number of employees per kilogram of product will not change significantly.

Appendix II Scale calculations

Hydrogen production rate:

$$264 \text{ ktons/year} = \frac{264 \times 10^6}{2,016 \times 365 \times 24 \times 3600} = 3.98 \text{ kmol/s}$$

Reaction equation:



The reaction equation shows that 9 moles of hydrogen are used per mole of propylene. It is now possible to calculate the propylene production rate which equals 0.442 kmol/s.

Propylene production rate:

$$0.442 \text{ kmol/s} = 0.442 \times (6 \times 1.008 + 3 \times 12.01) = 18.58 \text{ kg/s} = 535 \text{ ktons/year}$$

The reaction equation also shows that 2 moles of carbon dioxide are used per mole of propylene, therefore the carbon dioxide consumption rate equals 1.33 kmol/s.

Carbon dioxide consumption rate:

$$1.33 \text{ kmol/s} = 1.33 \times (12.01 + 2 \times 16.00) = 58.31 \text{ kg/s} = 5.04 \text{ ktons/day}$$

For an estimated efficiency of the adsorption process of 50%, the generated air flow has to achieve at least 10.08 ktons CO₂/day = 229,013 kmol/day. The molar volume of a gas at standard conditions is 22.5 m³/kmol, which results in 229013 kmol/day = 0.00515 km³ CO₂/day.

Air flow rate:

Air contains 370ppm of carbon dioxide, so the airflow becomes

$$\frac{0.00515}{370 \times 10^{-6}} = 13.92 \text{ km}^3/\text{day}$$

Appendix III Scenario costs

Hydrogen costs:

Hydrogen production rate (2500MW thermal):	264 ktons/year
Equivalent in propylene production rate:	535 ktons/year
Cost of hydrogen ^[14] :	1.42 US\$/kg

The cost of hydrogen is:

$$\frac{1.42}{535 \times 10^6} \times 264 \times 10^6 = \mathbf{0.70 \text{ US\$/kg propylene}}$$

Carbon dioxide costs:

Scrubber

Investment costs scrubber ^[11] :	10 million US\$
Depreciation period:	10 years
Equivalent in propylene production rate:	535 ktons/year

The costs of the scrubber are:

$$\frac{10 \times 10^6 / 10}{535 \times 10^6} = \mathbf{0.002 \text{ US\$/kg propylene}}$$

Extraction

CO ₂ production:	229,000 kmol/day
Enthalpy thermal decomposition of calcium carbonate ^[10] :	179.2 kJ/mol
Costs nuclear energy ^[9] :	0.03 US\$/kWh
Propylene production:	535 kton/year

Energy needed for CO₂ adsorption:

$$\frac{229,000 \times 365 \times 179.2 \times 1000}{60 \times 60} = 4,160,675,556 \text{ kWh}$$

Costs for CO₂ adsorption:

$$\frac{4160675556 \times 0.03}{535000000} = \mathbf{0.23 \text{ US\$/kg propylene}}$$