# Biomass as Feedstock for the Industry

Road to Perdition or the Promised Land?

# Colophon

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Rotterdam University
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The Netherlands



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## Road to Perdition or the Promised Land?

**Inaugural Lecture**

**Ad de Kok**

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# 1. Introduction

Today a lot is already possible in the area of biotechnology. However, not everything is practical! Not everything is practical, because the appropriate technology has not been developed fully (or has not been developed at all) or the economies of scale are not present and costs are too high. The implementation of new technology takes a very long time, sometimes decades. Last but not least, the available fossil resources still set the standard for competition. Oil is too cheap to make the transition to a bio-based economy a real 'burning platform'.

As Willem Schoonen[1], Editor-in-chief of *Trouw*, wrote:

*"The proponents of the drive towards sustainability form a movement which the Trouw editors, Lodewijk Dros and Wilfred van de Poll, have examined in their green catechism. They expose a religious undercurrent amongst the pioneers of green thinking. Sustainability as a green religion. One might perhaps expect that these two theologians would be happy with their discovery. However, the opposite is true: they are suspicious of the vision of the 'visionaries' of the Sustainable Hundred, such as Klaas van Egmond, Herman Wijffels and Queen Beatrix. I find the religious aspect attractive. Perhaps even indispensable. If the drive towards sustainability has a religious character, it cannot pretend to be entirely scientific. One may regret that, but I think it is an advantage. Science on its own would be impoverished. After all, why would one only take action if scientific proofs are available of, for instance, the role of mankind in global warming? Why should changes in behaviour only occur on rational grounds? There may be so many more grounds: beauty, pleasure, compassion, a conviction that one is doing what is right. Or, indeed, religion."*

Schoonen argues that changes in lifestyle and measures to prevent pollution and reduce emissions come at a price. If they generate more revenues than costs, generally speaking we would implement such measures. We would be even more inclined to do so if they were not accompanied by any damage to any ecosystem.

Scientific proof justifies these costs. If, on the other hand, that proof cannot be provided, then spending large sums of money on environmental measures is not deemed justifiable and any action is stalled. This is fact-based politics.

Schoonen uses our knowledge of the ozone layer as an example. Chemists proved what no-one thought was possible. Freons, substances that do not react with any other substance on the ground, do react high up in the atmosphere. This had dramatic consequences for the ozone layer that protects life on earth from UV radiation from the sun. The proof was so overwhelming that the freons were banned in record time. This was a successful example of fact-based politics.

*"Facts are the air of scientists. Without them you can never fly"*

**– Linus Carl Pauling, Nobel Prize Winner in Chemistry 1954**

However, fact-based politics may also be a weakness. For years scientists of the Intergovernmental Panel on Climate Change (IPCC) evaluated the risks of climate change and the influence of mankind on climate. Then, when painful measures had to be taken, politicians used any doubt or uncertainty expressed by the IPCC to delay or cancel the necessary measures. Uncertainty, inherent in any scientific study, became a political fact.

Science generates evidence that can only be used to a certain extent by politicians. If they really wish to promote sustainable development then they require more than mere scientific facts. They have to have the power to make clear that the path to sustainability is the right one for mankind, despite the fact that all scientific evidence is not (yet) available.

The transition towards a more bio-based economy is the right path to sustainability for mankind. However, it will be a path full of hurdles, disappointments and setbacks – a path that will require tenacity and conviction, and a belief in a positive outcome.

In spite of this perhaps rather sobering start, this lecture is not a negative narrative. It is a realistic one, one that highlights the many challenges and opportunities ahead of us. It is a narrative with some answers, but probably with as many new questions.

Hopefully it is also a wake-up call, because the worst conceivable scenario is to 'wait-and-see'. The fossil era is coming to an end. Shale gas and shale oil will also not change that. Mankind needs to be prepared for this. The good news is that we still have time – time to develop new technologies, to develop new legislation (or adapt existing legislation), and to change the mind-set of the general public and policymakers.

In Chapter 2 a number of economic and societal factors are described that impact on the transition to a bio-based economy, in general, and in the Netherlands, in particular. Chapter 3 describes the transition to a bio-based economy and is followed by critical success factors and issues (Chapter 4) and the opportunities for the Rotterdam area in Chapter 5. What this means for the education system and the research focus of Research Centre Mainport Innovation (RCMI), the Mainport Innovation Research Group, is described in Chapters 6 and 7 respectively. Chapter 8 then puts the discussions around the bio-based economy within a time perspective and emphasises why it is important to stay the bio-based course, despite many distracting external factors and developments.

Throughout the chapters, ten statements are postulated that are based on the text and are meant as food for thought and further discussion.



# 2. Why a Bio-Based Economy?

In the literature one can find various arguments for the transition to a bio-based economy. The five most important arguments are:

- **Economic opportunities** – an important argument for the bio-based economy is the opportunities it offers Dutch companies that are traditionally strong in agriculture, the agrifood industry and the chemical industry.
- **Sustainable production** – society's growing demand for sustainable products and services is another argument for the transition to a bio-based economy. In the ideal case, the development of a bio-based economy leads to the closing of cycles: no more waste, and production is $CO_2$ neutral.
- **Climate change** – the use of fossil fuels has led to an increase in atmospheric $CO_2$, which is seen as one of the most important root causes for global warming. Biomass is seen as a $CO_2$ neutral feedstock. Through the use of biomass, $CO_2$ emission is compensated by $CO_2$ storage during plant growth.
- **Security of supply** – the exploitation of fossil feedstock supplies exceeds the exploration and development of new sources. This means that over time the fossil feedstock supplies will be exhausted and long before then oil and gas prices will increase.
- **Independence** – The Netherlands and Europe are dependent on the Middle East and Russia for the majority of the fossil feedstock supply. This creates unwanted dependence on politically unstable countries and countries that use feedstocks to exert political pressure. The use of bio-feedstocks reduces this dependence.

A number of these arguments are discussed in more detail in the remainder of this chapter.

## 2.1 Chemical Industry in the Netherlands

Traditionally, the European Union is a strong contender in the global chemical industry. It produces over 21% of world sales with 20% of global industrial GDP and 11% of world population.[2]

The position of the Netherlands (Exhibit 1) is even stronger: it has 2% of world production with only 0.2% of the world's population. This makes the chemical industry a critical component of the Dutch economy. After the food industry, it is the largest industry in the Netherlands with €51 billion in combined revenues, 63,000 employees in 2010 (of which one third with a degree from a research-based university or a university of applied sciences), investment in R&D of €1.2 billion and a wide range of supplier and customer industries. The chemical industry directly generates almost 3% (€14 billion) of the added value of the Dutch economy and represented approximately 20% (€71 billion) of Dutch exports in 2010, as compared to imports of €47 billion, resulting in a positive contribution to the national trade balance of €24 billion. This is by no means insignificant.


Exhibit 1: The Dutch chemical cluster, *adapted from reference 3*

In the period from 2030 to 2050, the northwest European region will seek to increase its strength through innovation, cooperation, and specialisation. It will be active in production across the value chain and in end-user markets that include fossil and bio-based feedstock. This trend will enable the chemical industry to continue to be a leading sector in generating wealth and jobs in the Netherlands.[4]

The balance between bio-based and traditional feedstock in 2050 will depend on which scenario[3] gains the upper hand: *Fragmented Future, Green Revolution, Abundant Energy or High-Tech World.*

We may see a **Fragmented Future** with limited innovation and regional trading blocs that scramble for resources. From its good starting position, the Netherlands will in this case dominate the relatively slowly growing European market. With a global economy growing only 2.5% CAGR through 2030 in this scenario and a severely smaller role of Europe, the Netherlands can still increase production by 1.6 times by growing its European market share from 10% to 12%.

Or there may be a **Green Revolution**, where large parts of feedstock originate from biomass. With its current network of chemical plants, its agricultural knowledge and the Port of Rotterdam, the Netherlands is well placed to become a bio-hub. Next to domestic biomass, it will process biomass from the large number of source countries that lack a strong domestic chemical industry. Examples are African countries and Ukraine. With global GDP growth of 3%, and a loss of global market share, the Netherlands can grow still by 1.6 times by 2030 in this scenario.

A third scenario is a world of **Abundant Energy**. This assumes large availability of energy sources with a limited greenhouse gas impact, e.g. a breakthrough in solar technology. A world with clean energy ($CO_2$ free) is the result. With cheap solar energy, demand for oil collapses, making naphtha based chemicals cheap. Economic growth will be unprecedented and the Netherlands will benefit from widely larger end markets. Chemical output in the Netherlands can grow almost threefold, driven



by strong end market sales and a higher European – though lower global – share of production.

Finally, chemistry may become technologically much more sophisticated (**High-Tech World**). There will be by an explosion in the number of scientists and engineers with ever better supporting information technologies. Bioengineers are able to select and model molecules in ways that were not held possible before, opening up new applications and increasing revenues for the industry. Processes are intensified, enabling asset light strategies and decentralisation with small scale plants next to large integrated complexes. These new technologies greatly enhance the industry's bargaining power in the raw materials markets. And they allow substantial market growth, offering the Netherlands opportunities for high market shares in selected applications. By 2030, Dutch production could almost triple based on a global chemical industry growing 5% CAGR and a constant global market share of 2.2%.

In the **Green Revolution** scenario, new forms of bio-based feedstock will be embraced. These will be different from today's first generation biomass that competes with food. Second generation biomass will be used, which will utilise non-edible material like straw, whole plant and wood, which contain polymers of plant cell walls (cellulose, hemicellulose and lignin). In addition, third generation biomass will be widely used. This will include algae specifically cultivated to be similar to oil-based feedstock. They will be biologically engineered to offer the same functionality as naphtha-based products, but with fewer processing steps or altogether new functionality. The industry will have reduced its dependence on naphtha, but naphtha will still be the main feedstock and its use will have grown in absolute terms.

By 2030 to 2050 the northwest European cluster will have made the changes to its asset base needed to process different sorts of feedstock for both bulk and specialty chemicals. By doing so, the industry will minimise its exposure to the risk of raw material supply, while simultaneously becoming more sustainable. With these changes, the industry will also offer a more diverse product output that supports a wide range of end-user markets, including health, food, and agribusiness.

In combination with the ports of Rotterdam and Antwerp, the northwest European chemical cluster will be Europe's hub, not only for oil and gas, but also for bio-based feedstock and residues.

## 2.2. Availability of Natural Resources

Macro trends, like the growing world population, scarcity of resources, shifting economic power, climate change will reshape the world. In response to these macro trends, the global chemical industry is changing as well.

Some trends will have a negative impact, like increased investment in production capacity in the Middle East and Asia. Others may very well have a positive impact on Europe, like the introduction of bio-based feedstock into the value chain, new enabling technologies and converging end-user markets. The grand challenges of today (Exhibit

2) have, directly or indirectly, a large influence on the Dutch economy in general and the chemical sector in particular. They are a threat for who ignores them. At the same time they represent opportunities for corporations and knowledge institutes to create their own future by developing new products, explore new markets and research areas, and develop new education.

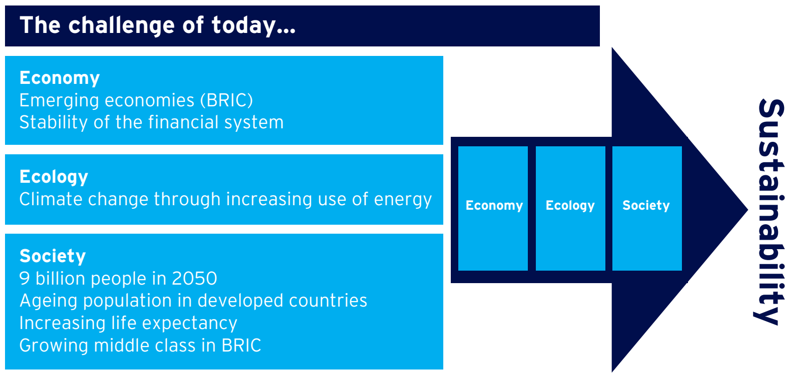



**Exhibit 2**: Grand challenges of today

**Our natural resources become scarce**
Worldwide the realisation is growing that the way mankind is growing the economy today puts too high a claim on the earth's resources.

Raw materials are being used at a rapid pace. Not only fossil materials, but also important chemical elements, such as precious metals, are becoming scarcer and/or exploitation is becoming more difficult (Exhibit 3). In order to keep this earth habitable for future generations, an economy that uses renewable resources and closed cycles will be needed.

*"Sustainability is to meet the needs of the present without compromising the ability of future generations to meet their own needs."*

**- World Commission on Environment and Development**

**We are running out of oil**
It is a fact that since 1964 an ever decreasing amount of oil has been discovered, despite improved exploration techniques. **Peak oil** is the point in time when the maximum rate of petroleum extraction is reached, after which the rate of production is expected to enter terminal decline.[6] In the literature various 'peak oil' scenarios are described. Campbell predicted that the peak would occur in 2010. Later studies (Harper, US Geological Survey) anticipate reaching peak oil conditions in the period from 2015 to 2035 (Exhibit 4).



Whether peak oil conditions are reached in 10, 30 or even 50 years, the fact remains that at the end of this century our oil reserves will be nearing depletion and alternatives will have to be developed before then. This does not mean that no more oil will be available, but the cost of extracting it is uncertain.

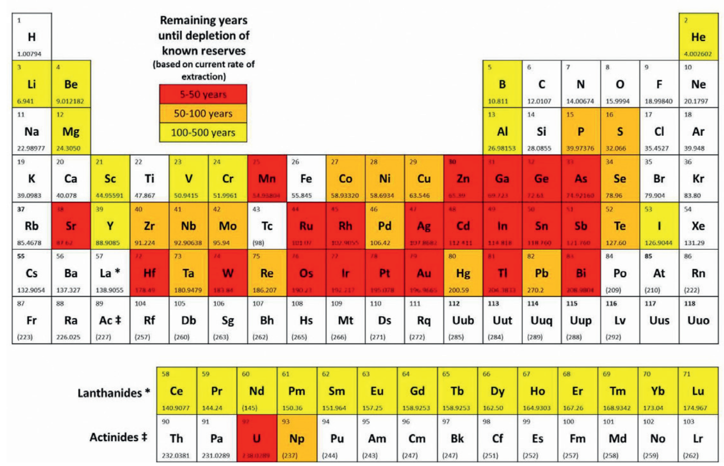



**Exhibit 3**: Years until the exhaustion of chemical elements, *adapted from reference 5*

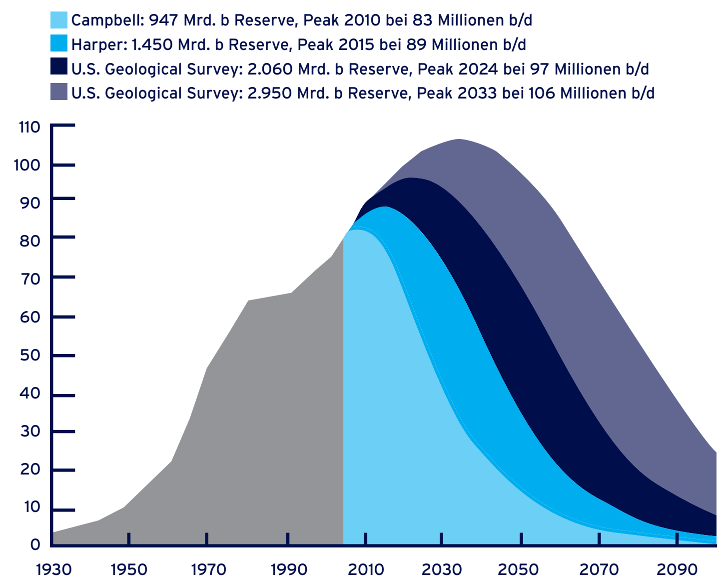



**Exhibit 4**: Peak oil conditions, *adapted from reference 7*

*"The Stone Age did not end because of lack of stone and the Oil Age will end long before the world runs out of oil"*

**- Sheikh Zaki Yamani, Former Saudi Arabia Oil Minister**

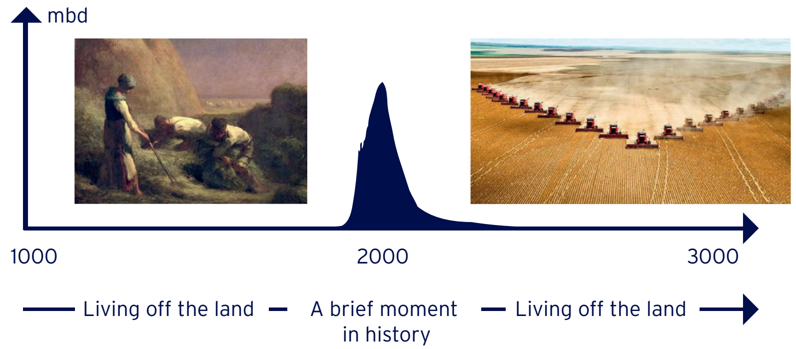



**Exhibit 5:** Living off the land, *adapted from reference 8*

For centuries, mankind 'lived off the land'. Then there was this 'brief moment in history' of a few hundred years that mankind based its entire economy on fossil fuels. And then… mankind will have no choice but to return to 'living off the land' (Exhibit 5).

**While our demand for energy is increasing**
Energy use is also a matter for concern. In the OECD (Organization for Economic Cooperation and Development) countries significant efforts have been and are being made to save energy.

A huge increase in demand for energy has occurred in the BRIC countries (Brazil, India, Russia and China). Demand has increased particularly in countries like China and India that have large populations and are experiencing significant economic growth. People in India and China also wish to have a share of the world's wealth and own the latest kitchen appliances, watch television and drive cars. At the moment China is the world's largest automotive market and is still growing at double digit rates.

*"… Two or three centuries from now one will look back on our civilization as a brief moment in history where in a period of about 250 years mankind based the whole economy on coal, oil and gas…"*

**- Feike Sijbesma, CEO DSM**



That the demand for energy is going to increase in the next decades is a fact. The world's current average consumption is 1.66 tonnes of oil equivalents per capita per year (Exhibit 6). An increase of 50% by the end of this century (Exhibit 7) is probably very conservative, given the economic development of China, India and Brazil.

## 2.3 Growth of the World's Population

The world's population will grow to approximately 9 billion people in 2050 (Exhibit 8). In the developed economies the population will age with gradual, but unavoidable, consequences for the labour market, healthcare and consumer demand. In countries like China, Brazil and India, a new middle class will emerge.

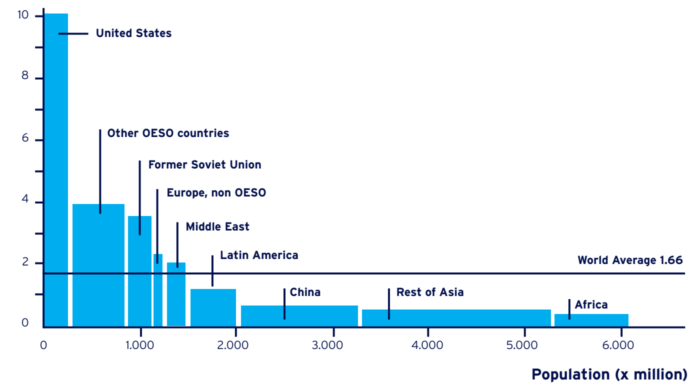



**Exhibit 6:** World energy use per capita[9]

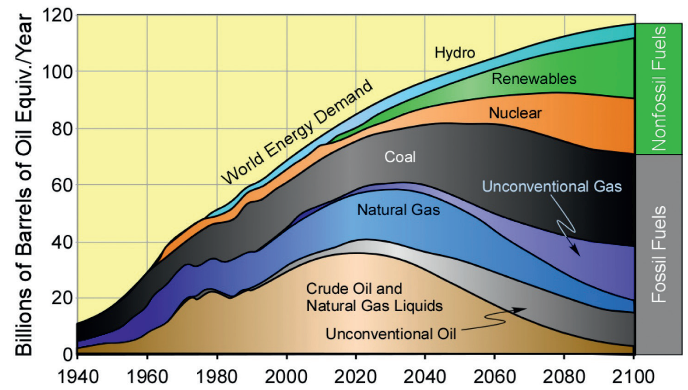



**Exhibit 7:** World Energy Demand, *adapted from reference 10*

More people with increasing life expectancy and higher consumption will push up the demand for raw materials, energy, water and food/feed. A lack of resources, including a considerable number of chemical elements, will give a (geo) political dimension to their availability and price structure.

*Every second the world population grows by 2.5 persons*

**– United Nations**

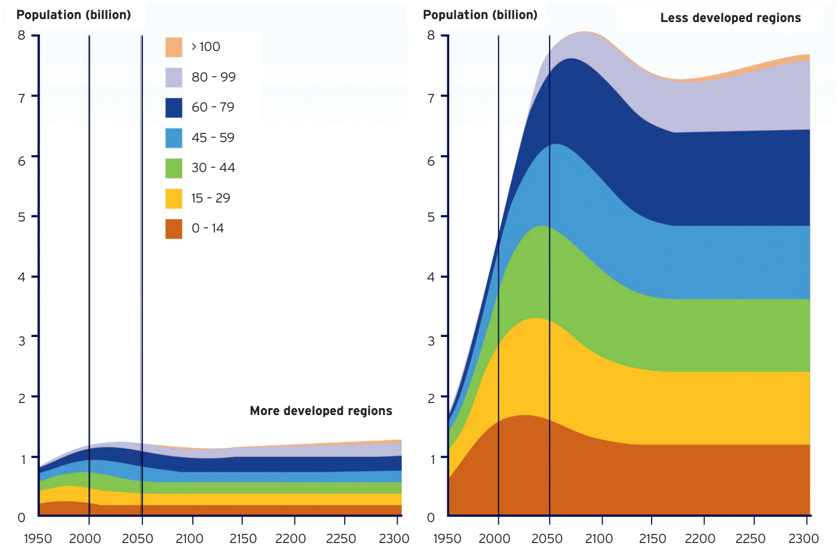



**Exhibit 8**: Growth of world population, *adapted from reference 11, p.44*

## 2.4 Globalisation and Emerging Economies

A growing population not only means greater consumption, but also greater competition. Emerging economies develop into formidable competitors, both through their corporations and through their development of knowledge and technology. This results in a shift in the production of bulk products to lower-wage countries. This in turn leads to defensive measures, such as import duties and import quotas. One of the most striking examples in this area is the import duty of €194 per $m^3$ on ethanol, one of the most versatile bio-based building blocks for the greener production of chemicals. Due to this import duty, imposed by the European Union, any project using imported ethanol as a feedstock is almost by definition a no-go with respect to its business case. There is therefore an urgent need for a 'level playing field'.

## 2.5 Climate Change

The strong increase in energy consumption and the massive consumption of fossil raw materials has resulted in increased $CO_2$ concentrations in the atmosphere. This increase is considered to be an important cause of climate change. The concern for climate change is expressed in laws and directives aimed at preventing emissions and stimulating the use of renewable raw materials. The rapid growth in shale gas, however, has made renewables comparatively less attractive and urgent needed, adding to the challenge.



DAVOS, Switzerland, Jan 25, 2013 (Reuters) – Climate change is back on the global agenda, with debate in the corridors at Davos given fresh impetus by U.S. President Barack Obama and U.N. Secretary-General Ban Ki-moon both highlighting it as top priority this week. Yet business leaders are still struggling to find the economic incentives to change current practices.

The World Economic Forum (WEF) has not held back in its own assessment of the dangers, with former Mexican president Felipe Calderon warning of "a climate crisis with potentially devastating impacts on the global economy". Christine Lagarde, managing director of the International Monetary Fund, summed it up for any Davos doubters: "Unless we take action on climate change, future generations will be roasted, toasted, fried and grilled."

# 3. The Transition to a Bio-Based Economy

A bio-based economy is an economy that obtains its raw materials mainly from living nature (biomass, 'green' raw materials), as part of a green or sustainable economy.[12] A highly developed bio-based economy uses renewable resources mainly for the production of chemicals and materials, in addition to energy, in a way that minimises competition with the food chain.

The bio-based economy will play an increasingly significant role in the chemical industry in the future and, although our industry will undoubtedly remain pre-dominantly based on petrochemicals in the coming decades, there is potential for greater use of bio-based feedstock (Exhibit 9).

*"The world needs sustainable energy, but renewable feedstock gives more than that. Sustainable energy sources such as wind and sun only provide us with electricity, but renewable raw materials give us chemicals and materials, and residues that can be transformed into bio-fuels."*

**– WTC Biobased Economy 'Naar Groene Chemie en Groene Materialen'[12]**


**Exhibit 9**: Traditional and non-traditional feedstocks, *adapted from reference 13*

The general public has bio-fuels in mind, not bio-materials, when talking about 'green' resources. There is, however, a big difference in volume between the energy and materials markets. The world uses approx. 100 EJ (E=Exa=$10^{18}$) in transportation fuels and, calculated on an energy basis, 8 EJ for materials.[12]

A US study[14, 15, 16] from 2005 showed that approximately 40% of the total energy used was used for industrial applications, and that approximately 3% of this 40% was used for the production of chemicals. In other words, only approximately 1% of the total demand for energy is used to convert fossil fuels into functional materials.

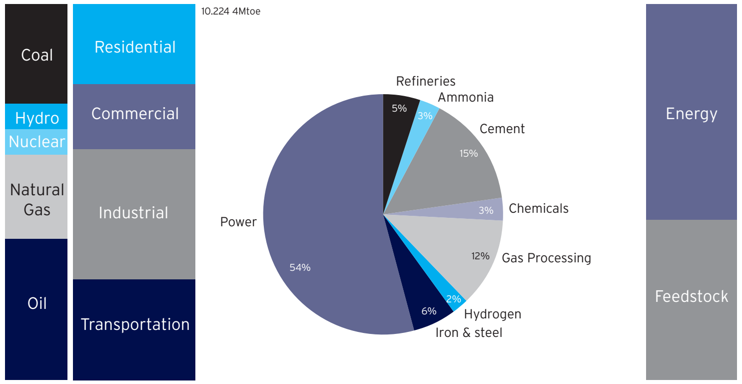



**Exhibit 10**: Energy and feedstock use for the production of chemicals, *adapted from reference 18*

Transitioning to 'green' substitutes for petrol and diesel is a completely different issue than changing to green substitutes for materials.

**Bio-refining**

In a bio-economy, in principle all forms of biomass pass through a refining process. Bio-refining can be compared with conventional refining, where oil is processed into a large spectrum of products, such as various fuels from diesel to kerosene, but also to feedstock for chemicals and plastics. In contrast to traditional refining, in the case of bio-refining the raw material is not oil, but biomass. The various potential process steps in bio-refining are shown in Exhibit 11. There are many desired raw materials. Some are already part of the economy, such as food products. Others already exist, but have little economic value, such as residue streams. Yet others only exist in concept at the moment, for example products from synthetically created bacteria. The ways to produce and process these feedstocks range from commonly used processes, such as incineration and gasification, to technologically more advanced treatments, such as industrial biotechnology and the use of synthetic biology.

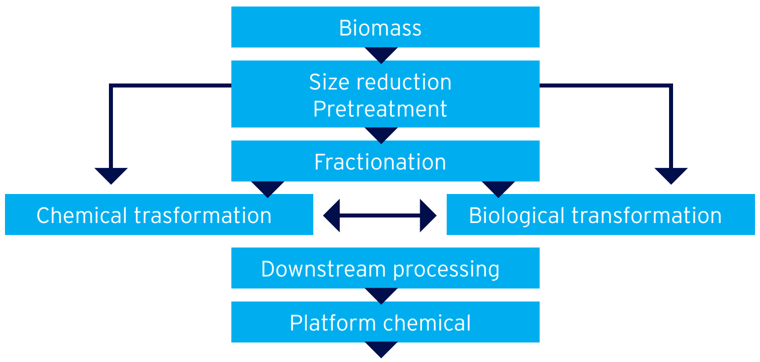



**Exhibit 11**: Principle of bio-refining, *adapted from reference 17*



For the Dutch government, the concept of cascading represents the essence of what bio-refining should deliver. Cascading means that products with the highest added value are isolated from biomass first, followed by products with lower added value with the residue finally being used for power generation (Exhibit 12). The secret is to transform all parts of plants through an application which generates the highest possible added value. Every part of the plant can be used. It is a process which generates no waste.

*"Bio refineries of the future will be able to extract novel, value-added compounds, like fine chemicals, and convert the remaining biomass into energy or building blocks for chemical synthesis, leaving only small amounts of waste whose inorganic components could be recycled for use as fertilizer.*
*Process technologies required for a zero-waste bio refinery will be available by 2020, at least at the level of semi-commercial demonstration plants."*

**- European Commission, 2007[6]. Rathenau Instituut, Den Haag, 2011[20]**

The isolation of high value-added components first from biomass is not always emphasised. Too often biomass programmes are born of the need for renewable transport fuels and that objective often has pride of place.

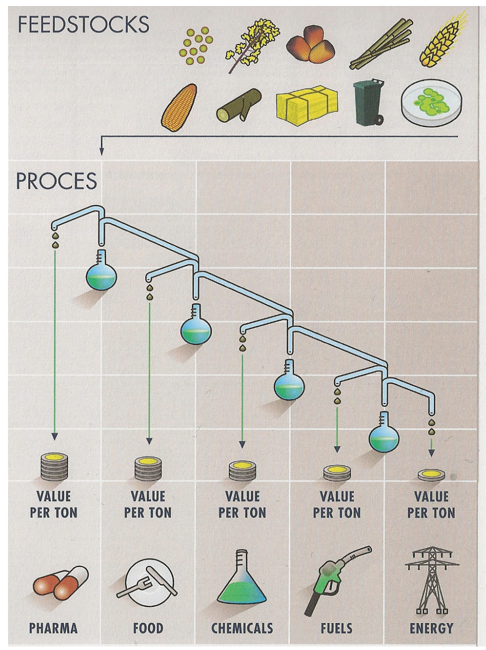



**Exhibit 12**: Cascading of biomass, *adapted from 19*

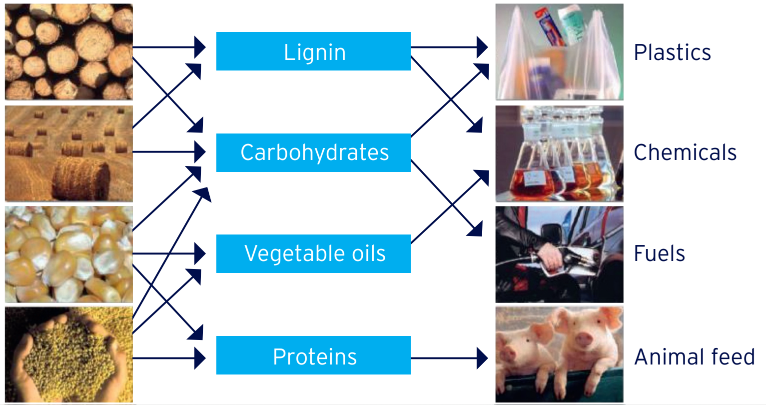



**Exhibit 13:** Potential product mix from biomass, *adapted from*[17]

More and more, however, the realisation is setting in that bio-refining can only be economical if a variety of products are produced (Exhibit 13).

Important criteria for the use of renewable materials in producing chemicals are energy content, the accessibility of the individual components of the renewable raw materials and the suitability of the individual components to form a basis for chemical value-added chains. See Exhibit 14 for the lignocellulose example.

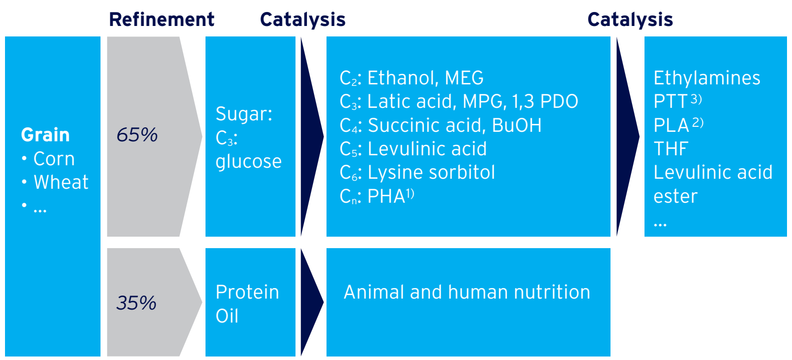



**Exhibit 14:** Value-added chain for lignocellulose, *adapted from reference17*

Today's chemical industry processes crude oil into a limited number of base fractions. Using numerous cracking and refining catalysts and using distillation as the dominant separation process, crude oil is refined into fractions such as naphtha, gasoline, kerosene, gas oil and residues. The relative volumes of the fractions formed depend on the processing conditions and the composition of the crude oil. The naphtha fraction is subsequently used as a feedstock for the production of just a few platform chemicals from which all the major bulk chemicals are derived. An important characteristic of the naphtha feedstock is that, unlike biomass, it is very low in oxygen content. The



majority of bulk chemicals, such as those produced in the Port of Rotterdam, can be produced on the basis of just six platform chemicals (ethylene, propylene, C4-olefins, and the aromatics benzene, toluene and xylene [BTX.).[21]

As illustrated in Exhibit 15, there are many conventional routes that can be integrated with bio-based feedstocks to either supplement or replace current petrochemical feedstock, such as ethylene, propylene and xylene.
Through fermentation of sugar, butanol can be produced. From lignin, aromatics can be manufactured. So the building blocks are there to transform the petrochemical industry into 'green' chemistry.

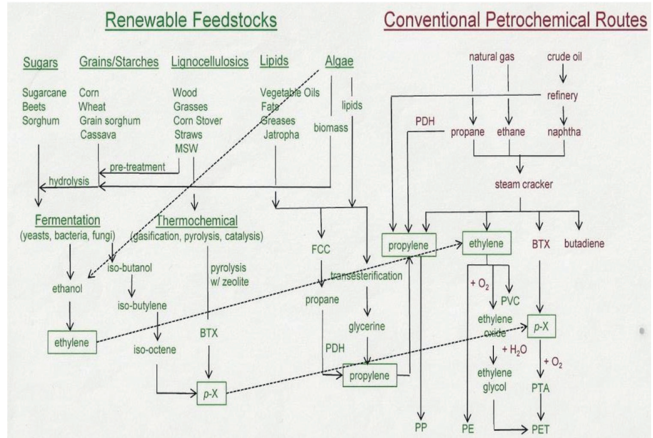



**Exhibit 15:** Renewable feedstock vs conventional petrochemical routes, *adapted from reference*[21]

The WTC (Wetenschappelijke en Technologische Commissie voor de Biobased Economy) describes three development phases for the bio-based economy[12]:

**Biofuels in the petrochemical infrastructure (2010 – 2025).**
This phase concerns the introduction of biochemicals into existing infrastructure. Examples are (bio) ethylene, (bio)methane, (bio)synthesis gas and (bio)methanol, (bio)propylene (from glycerin), butanol and aromatics.

**Full utilisation of the potential of catalysis, enzymes and fermentation, transition to the agrisector (2015 – 2040).**
The Netherlands is the world leader in the areas of catalysis and industrial bio-catalysis. These competencies are extremely important, not only in relation to petrochemical technologies, but also in the transition to bio-based technologies.

**Bio-refining, utilisation of the full complexity of bio-feedstock (2020 – 2050).**
The true value of 'green chemistry' will surface in this phase: the isolation of valuable products from plants, where food/feed, chemicals and fuels will be produced from second generation biomass. Only then can we speak of bio-refining, where, according

to the value pyramid (Exhibit 12), first the products' highest added-value components are isolated (amino acids, proteins, peptides).

The year 2050 seems to be a good target year to complete the transition to green chemistry.[22]

*"Ten percent of chemical feed stock is already coming from renewable sources"*

**– Stichting Bio-Wetenschappen en Maatschappij, Cahier 34 maart 2010, biogrondstoffen**



# 4. Critical Success Factors and Issues

## 4.1 Economic Aspects

The concept of sustainability has generated much discussion and has been introduced incrementally into corporate thinking. However, the implementation of changes in industrial processes, products, and practices has progressed at a slow pace. One reason for this is the enduring myth that economic profitability must always be sacrificed to achieve environmental goals.

*"You can make anything from lignin, except money…."*

**– Anonymous, 2011**

This myth may or may not be true. However, the economic profitability of bio-processes is probably more closely related to technology and scale than to environmental goals.

**Scale matters……. or does it?**

"Cheap" feedstock does not always result in cheap chemicals. Scale may be a limiting factor. In the traditional process technology it has been known for many years that there is a relationship between production scale and production costs. See Exhibit 16 for a typical relationship for US production industry.

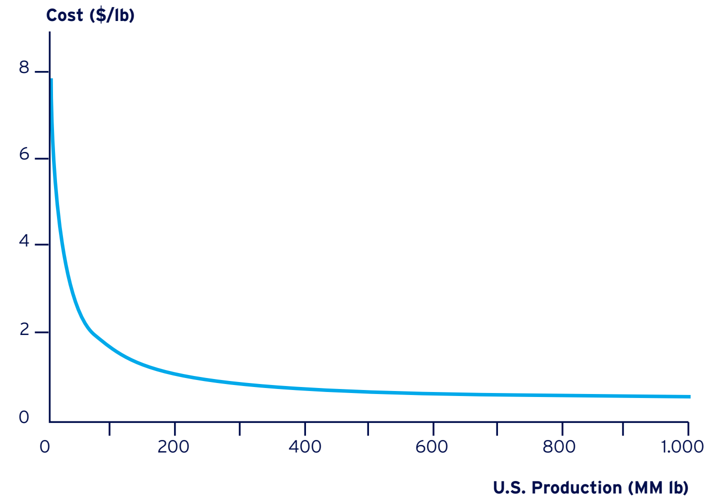



**Exhibit 16:** Economy of scale in the chemical industry

However, in traditional process technology one reduces complex mixtures to the smallest possible building blocks (methane, ethylene and propylene), eliminating already present molecular functionality, and one then starts to rebuild new functionality into chemicals from there. This obviously requires a lot of energy and is therefore very capital intensive. Consequently, large manufacturing plants are needed to recover capital expenditure.

*"Economy of scale is losing its competitiveness"*

**– Johan Sanders, Wageningen Universit, 2012**

Johan Sanders, Professor of Bio-based Commodity Chemicals at Wageningen University, argues that the capital cost can be reduced by using all biomass components at their highest value, by not destroying the functionality already present in biomass. Its (molecular) structure is much more valuable than caloric value. Reduced capital costs are essential to speed up innovation and to make it possible to benefit from small-scale production without the disadvantages of small-scale production. In other words, the cost-capacity curve for the traditional processes may not hold true for bio-based processes and comparing the Cost of Manufacturing (CoM) of bio-based (pilot) plants with that of existing fossil technology, which has been optimised and fine-tuned for decades, may not be appropriate.

Many 'green' technologies still need to be developed and, at least initially, will be more expensive due to the limited scale of production and higher CAPEX requirements due to the lower energy density of the biomass feedstock. Crude oil is three to five times more energy dense than biomass. To produce the energy equivalent of one oil refinery, 60 ethanol plants would be needed. The capital required to convert crude oil to a MM Btu (1.05435 GJ) of useable energy is about half that of biomass, $164/ MM Btu ($155/GJ) versus $321/ MM Btu ($304/GJ) (Exhibit 17). Feedstock will also not be available free of charge. It will have its own supply/demand dynamics and price structure, as fossil feedstock does today.

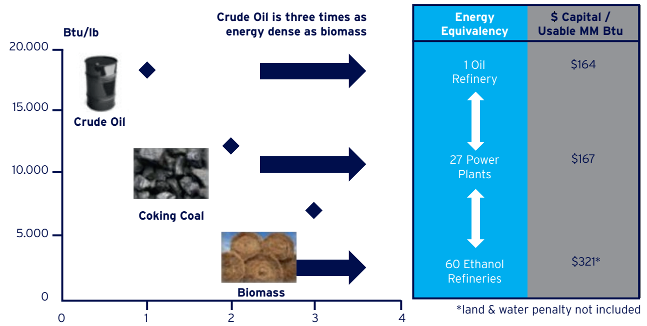



**Exhibit 17:** Capital 'density' of fossil versus bio-feedstock, *adapted from reference 25*



**Can we afford to switch?**

A study by Dow Chemical[18] has shown that replacing the world's fossil ethylene volume by bio-ethylene, based on bio-ethanol, will require between $200 billion and $400 billion in capital (depending on technology), Exhibit 18.

In 2006, the combined annual capital expenditure of the top 50 chemical companies was around $60 billion, of which probably less than half was spent on new facilities. Even if one assumes that all this capital would be directed to building new bio-ethanol/ bio-ethylene capacity, it would take an absolute minimum of 10 years to convert the world to this platform molecule.

It is more realistic to expect that it will take at least two generations to convert. With the current emphasis on shale gas and shale oil and the lack of a 'burning platform' to move to bio-ethylene, it may take even longer. Today bio-ethylene is around two times more costly than its fossil counterpart (Exhibit 19). Bio-ethylene's cash cost is $1200/ MT, while the US average for fossil ethylene is $650/MT. Obviously there is not much incentive to change if these are the economics of the industry.

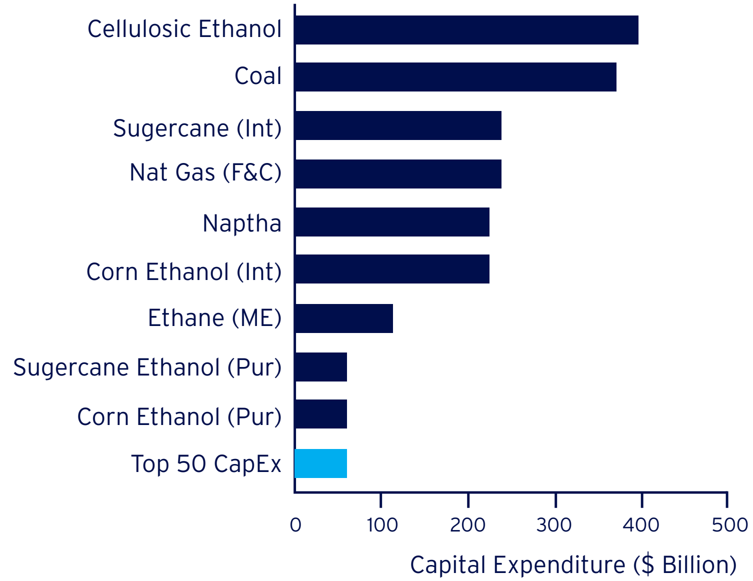



**Exhibit 18:** Replacement capital requirement for bio-ethylene, *adapted from reference 18*

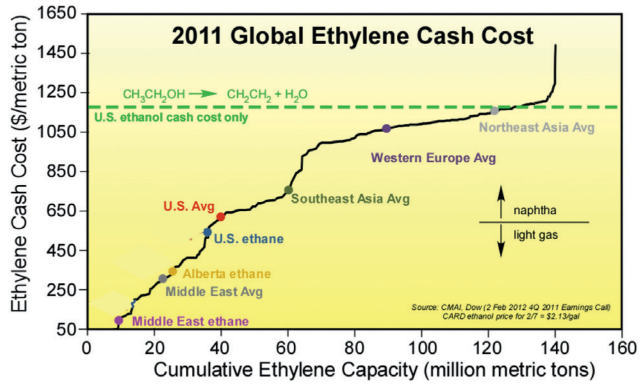



**Exhibit 19:** 2011 Global ethylene cash cost, *adapted from reference 38*

## STATEMENT 1

**The cost of switching from a fossil-based to a bio-based economy is huge and it will take several decades to complete.**

Exhibit 20 shows a cash cost indifference analysis for ethylene from fossil and renewable commodity feedstock, illustrating how biological feedstocks rarely offer a cost advantage over conventional feedstock. Ethylene from petroleum is taken as a surrogate for market ethylene and its cost is higher than current production from natural gas liquid cracking.

The line represents approximate cost equivalence for ethylene production. For the 1,539 days shown, crude was favoured over corn (blue points) for 1,084 days. Commodity sugar (red points) was never cost competitive.

Chemicals are made from purchased commodities today. These are purified from fossil resources. Purchased commodity agricultural and forestry derived feedstocks cost more than the incumbents. Unless consumers are willing to pay more, companies cannot afford to switch. Often the argument is used that a 'green' premium can be expected, meaning that the product can be sold at a higher price because of its 'green' image.



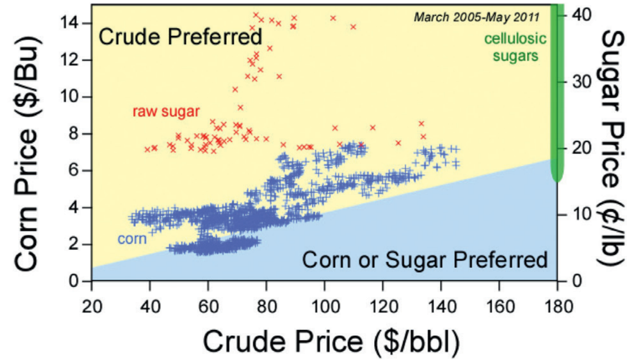



**Exhibit 20:** Cost equivalence for ethylene, *adapted from reference*[25]

This may only be true for some niche applications and/or only for a limited period of time. A study conducted in North America in 2011 (Exhibit 21, reference 26) revealed that in 2010 only 16% of consumers are willing to pay a premium of 20% for products which are made in an environmentally friendly and sustainable way. Of the total number of respondents, 69% answered that their purchasing behaviour was mainly determined by price.

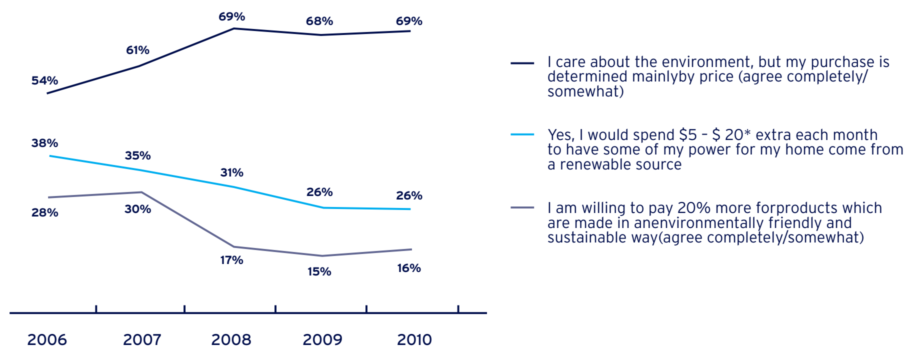



**Exhibit 21:** Consumer behaviour in relation to a 'green premium', *adapted from reference 26*

## STATEMENT 2

**Bio-commodities are too expensive today.
Green product premiums are small and only temporary.**

## 4.2 Technology Aspects

*"Too much hype for the possible, not enough focus on the practical."*

**– William F. Banholzer, CTO Dow Chemical, 2011**

The strategy in bio-refining is to use the already existing molecular functionality, instead of breaking down the molecule to synthesis gas (carbon monoxide and hydrogen) and rebuilding from there.

Exhibit 22 shows the oxidation states of the various fossil and bio-feedstocks. Every change in oxidation state requires energy, hence capital. Technologies that require multiple oxidation/reduction steps (the *oxidation state whiplash*) are economically challenging as a result and the number of steps should be minimised.

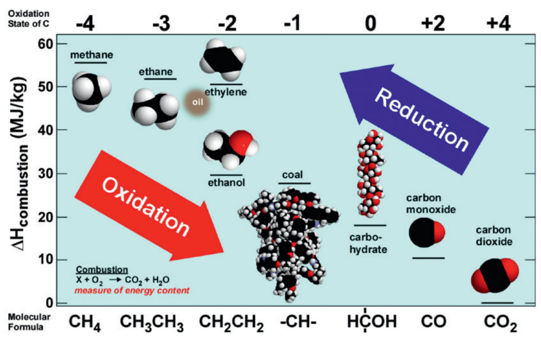



**Exhibit 22:** Feedstock oxidation states, *adapted from reference 24*

This requires a broad technology portfolio to manufacture chemicals from renewable resources:

- development of robust processes that accommodate multiple feedstock streams;
- efficient refinery, i.e. breakdown and fractionation of the biomass;
- development of selective catalytic processes for the transformation of carbohydrates; and
- better recovery and purification technology for diluted aqueous solutions.

**STATEMENT 3**

**Efficient, cost-effective refining and catalysis are key technologies to be developed.**



## 4.3 Is There Enough Land?

The demand for biomass feedstocks is likely to increase in the coming years. Will there be enough to feed 9 billion people AND provide energy, fuel, chemicals and materials?

Today's biomass use for food (incl. feed) is 4,000m to 5,000m MT, for wood, paper, cotton around 2000m MT and as wood for cooking 4,000m MT. If, in 2050, we wish to base 30% of our energy needs of 600 to 1,000 EJ on biomass, another 20,000m MT (20 billion MT) will be needed. Bio-based bulk chemicals will require another 2,000m MT of biomass[27].

NNFCC, the UK's national centre for bio-renewable energy, fuels and materials, estimates that the world's primary demand for energy is between 600 and 1,000 EJ (exa = 1018) per annum, while the sustainable biomass potential is estimated to be between 200 and 500 EJ per year. In other words, the world's demand for energy will exceed the sustainable supply of biomass (Exhibit 23).

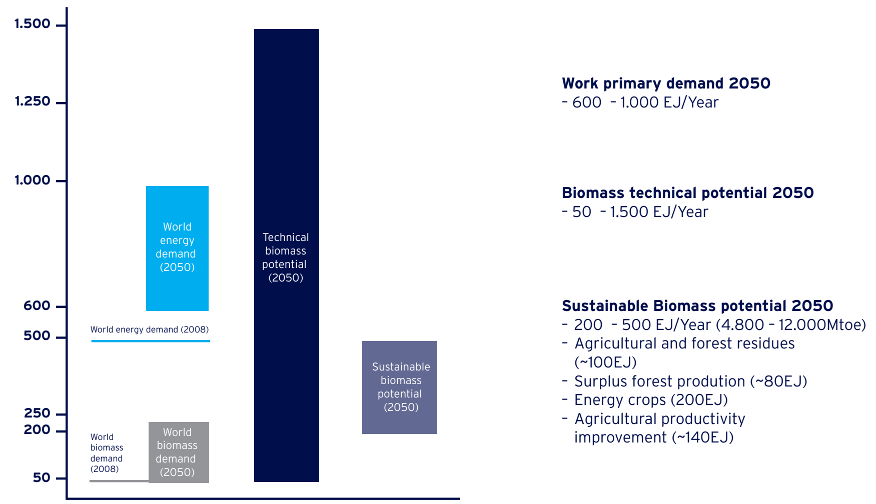



**Exhibit 23:** World sustainable biomass supply 2050, *adapted from reference*[28]

A study by BASF (Exhibit 24) comes to the conclusion that "30% of the arable land will be needed to meet only 10% of the oil demand in 2030". This land use will also compete with the cultivation of food for a future global population of 9 billion.

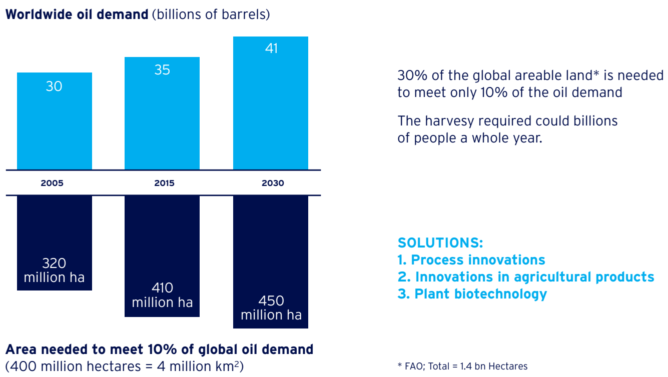



**Exhibit 24:** Renewable resource quantities, *adapted from reference 29*

Already today the 'food versus fuel' debate is one of the most important socio-economic issues in the transition towards a bio-based economy. Yield increases are therefore urgently needed. Significant steps forward have already been taken and will be taken in the future. In north-western Europe, where sugar yield in 2007 was 7 MT/ha sugar beets, it is double that today and is predicted to increase further to 20 MT/ha in 2020. Significant efficiency improvements can also be made in the food chain itself. Today about one third of the 654 million MT of food produced for human consumption in Europe is wasted!

*"205 Million MT of European food production of 654 million MT is wasted. 70 million MT of food is wasted by consumers..."*

**- Wageningen University, 2011**

## STATEMENT 4

**World energy demand will exceed sustainable biomass supply.**

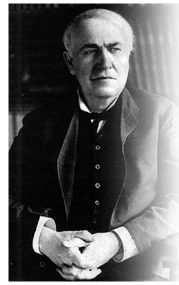
A new approach is the move to third generation bio-crops, such as algae or sea-weed, and dedicated 'aqua biomass farms'.[30] Compared to corn, the ethanol yield can be increased by a factor of 20 when moving to algae.

It is clear that the solutions will need to come from a mix of options: new technologies for processing biomass, improved crop yields, less waste, dedicated energy crops, ... but even then it is unlikely we will be able to provide for our energy, fuel and materials needs in a sustainable way.



*"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."*

**- Thomas Edison, 1931**



Solar energy totals around 5,000,000 EJ per year. As mentioned earlier, human demand for energy is in the order of 600 to 1,000 EJ. Plants need 5,000 to 6,000 EJ per annum. In other words: the sun provides enough energy to cover the world's energy needs for an entire year in less than a day!

Biomass is nothing else than recently stored solar energy. Solar energy must inevitably become a bigger part of the total solution.

*"We will harness the sun and the winds and the soil to fuel our cars and run our factories"*

**- Barack Obama, Inauguration Speech, January 2009**

## STATEMENT 5

**More and more energy will have to be supplied in the form of electricity from the sun, wind and water (in addition to the smart use of fossil sources). Biomass will be used primarily for chemicals and materials.[12]**

### 4.4 Shale Gas: Threat or Opportunity?

That the big oil companies are sceptical of green chemistry and the bio-based economy is a known fact. 'Green' chemists, on the other hand, are convinced that in the next thirty years a large percentage of the bulk chemical processes will have to be converted to their 'green' equivalents, with ethanol and succinic acid as the first chemical building blocks.[31] However, the oil companies have pulled a new trump card, namely the extraction of chemical building blocks from shale gas.

*"There's no doubt that we're seeing an industrial revolution taking place because of the shale revolution."*

**- Ed Morse, Global Head of Commodities Research at Citigroup**

Not all that long ago, one of the 'big oils' announced in NRC Handelsblad, that 'we' have shale gas for the next 250 years in such large quantities and at such low fixed cost that ethylene can be produced as a chemical building block for the chemical industry for many, many years to come. This does not have much to do with moving to a bio-based economy, but that is not their core business. Their core business is to supply the world with sufficient fossil fuels.

The United States, in particular, is active in the area of shale gas, but China is also not sitting still and in Europe the discussion around shale gas is also heating up. This is certainly something to keep an eye on, if the bio-based economy does not wish to die a premature death. To promote shale gas, to some extent the available reserves and supposed low cost[33] of shale gas is being exaggerated, both inside and outside the Netherlands.

In the case of the Netherlands, shale gas reserves are highly uncertain, ranging from a couple of years to about 10 years.[34] The lifespan of a shale-gas well is limited, so one has to keep drilling to maintain production. This makes it a fairly expensive form of energy that requires considerable investment of funds and government subsidies, money that could be spent on more sustainable solutions.

The main concern, however, is the environmental impact. Pollution, be it pollution of the soil, water or air, is extremely expensive. Since the 1980s many millions of euros have been spent in the Netherlands on remediation of polluted soil left behind by previous generations. To be more precise, for the period 1997 to 2023 19 billion euros has been reserved to control the problem and to remediate 175,000 heavily polluted locations.[35]

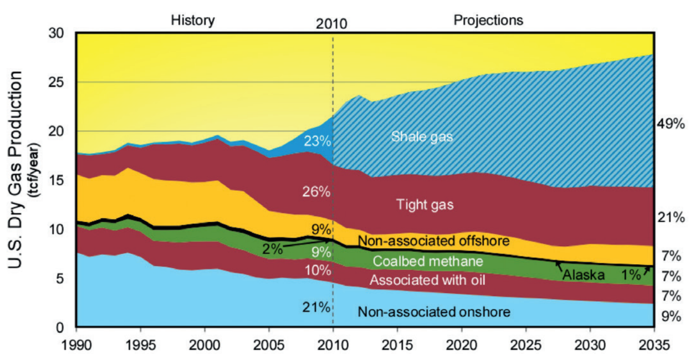



**Exhibit 25**: Projected US dry gas production 2010 – 2035, *adapted from reference 36*



*"We have a supply of natural gas that can last America nearly 100 years, and my administration will take every possible action to safely develop this energy."*

**- Barack Obama, 2011**

**What is hydraulic fracturing?**
Hydraulic fracturing,[32] or "fracking," is a resource recovery technique used to extract natural gas stored in geological formations. Used in limestone and sandstone gas deposits since the 1940s and in shales since the 1970s, fracking involves drilling through permeable rock expansions and pumping in a combination of water, sand, chemical lubricants and "propants" to keep the induced fractures open for gas recovery.

*"Every euro invested in fossil technologies will cost society 2 euros. Every euro invested in sustainable technologies will create 3 euros...."*

**- Jan Rotmans, 'Watt Nu?, 2013**

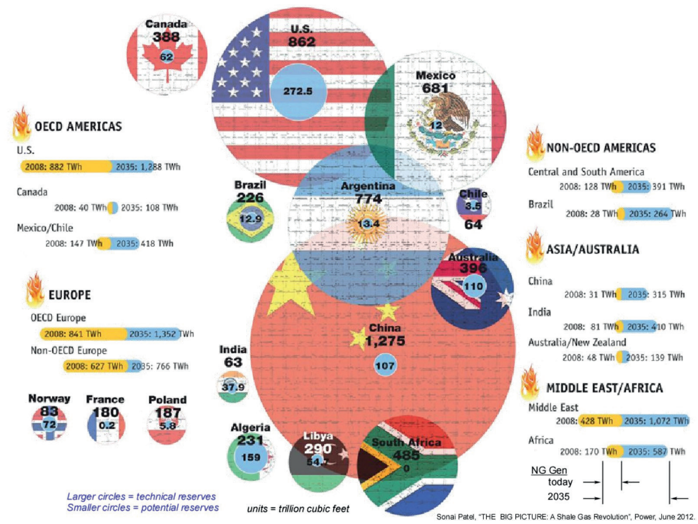



**Exhibit 26**: **Technically Recoverable Shale Gas Resources**, adapted from reference 34, 37

**STATEMENT 6**

**Shale gas is potentially a big step back in time as far as the environment is concerned. The so-called shale-gas revolution is not a revolution, but amounts to using up the last fossil fuel reserves, which is what we have been doing up until now.**

**Shale Gas as an opportunity?**

The shift to more shale gas as a feedstock for ethylene in the US, China and other parts of the world will result in a shortage in the availability of aromatic by-products (Exhibit 27). The implication of this is that the availability of propylene, butadiene and benzene will decline. Today, no bio-derived aromatics exist. The famous 'plant bottle' market, Coca Cola's drive for a 'green' PET bottle, is begging for the availability of bio-based PTA (Purified Terephtalic Acid).

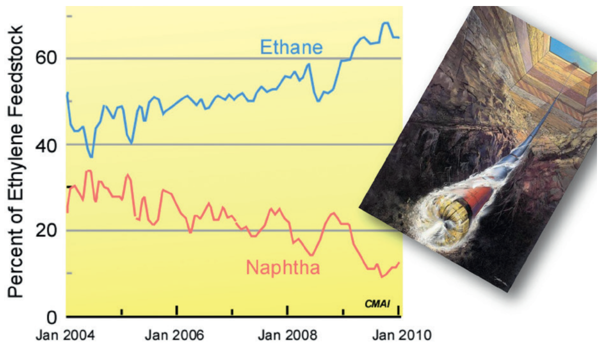



**Exhibit 27:** US trend in ethylene feedstock, adapted from reference 37

Also the conventional fossil-based economy is looking for alternative sources of aromatics. There is a discrepancy in the growth of the acetone market compared to the phenol market (both of which are produced from cumene), since the phenol market is growing at a far faster rate.

In summary, the conventional fossil-based and bio-based economies are looking for alternative sources of aromatics and this could prove to be a significant opportunity for the bio-based economy. However, technologies involving the direct isolation of aromatic building blocks from biomass, or the conversion of sugars or lignin into aromatics, are still in their infancy. The production of bio-based aromatics will also need considerable effort in the area of R&D, followed by demonstration and implementation plants. The competition is now open for the development of the most sustainable and economical process or combinations of these. $C_5$-$C_6$ sugars can be fermented, converted, thermally treated, hydrocracked etc. Lignin can be dissolved, hydrolysed, fractionated, separated into the traditional chemicals, such as phenol, butadiene, toluene and xylene, but these new technologies, which are still to be developed, could also be potential source of new molecules which could serve as building blocks, opening up new horizons.



The shale-gas debate is not over yet, and certainly not in the Netherlands. Both proponents and opponents avail themselves of every opportunity to bring their views and arguments to the attention of the general public and politicians. A selection of recent articles can be found in references 38 to 41.

**STATEMENT 7**

**Corporate investments in bio-ethylene as a bio building block for bio-chemicals and bio-materials are not very likely at present given today's focus on shale gas and shale oil.**

# 5. Green Chemistry in the Rotterdam Area

Rotterdam will be *the* location in 2030 where the transition to a bio-based economy will be in full swing. Corporations will exchange feedstocks and intermediates, integrating green and fossil chemistries. On the recently inaugurated Maasvlakte 2, there will be space for new bio-based chemistry and it will be possible to process large quantities of biomass (Havenvisie 2030[19]).

Van Haveren et al presented an extensive review of the opportunities for bulk chemicals from biomass[22] in the Rotterdam Area. Their conclusion at the time (2008) was that "*biomass routes are expected to make a significant impact on the production of bulk chemicals within 10 years, and a huge impact within 20 – 30 years*" and that "*in the Port of Rotterdam there is a clear short term (0 – 10 year) substitution potential of 10 – 15% of fossil oil-based bulk chemicals by bio-based bulk chemicals, especially for oxygenated bulk chemicals, such as ethylene glycol and propylene glycol, isopropanol and acetone, butylene and methylethylketone.*"

Glycerin, as a by-product of biodiesel production, was seen as a very favourable short-term option for the production of glycols in the Port of Rotterdam. In the mid-term (10 to 20 years) a potential was identified for the bio-based production of ethylene, acrylic acid and N-containing bulk chemicals, such as acrylonitrile, acrylamide and ε-caprolactam. Future bio-refineries will serve as stepping stones towards the chemicals mentioned above.

Exhibit 28 illustrates the potential bio-based industry in the Rotterdam area. First generation feedstocks (soy, rape, palm, sugarcane, wheat and corn) are converted into vegetable oils, which in turn are converted into methylesters (bio-diesel) with glycerin as a by-product, a valuable starting point for chemicals.

Bio-ethanol is a versatile building block for chemicals: bio-ethylene (through dehydration), as the starting point for the ethylene product chain; bio-butadiene (through aldolisation), as the potential starting point for the bio-propylene product chain; and bio-benzene, toluene, xylene (bio-BTX) through pyrolysis and ZSM catalysis, as the precursors of the bio-aromatics product chain. See also Exhibit 15.

Bio-ethanol is already produced in significant quantities in the Rotterdam area. Bio-diesel is already present, and so is the by-product glycerin (Exhibit 29).

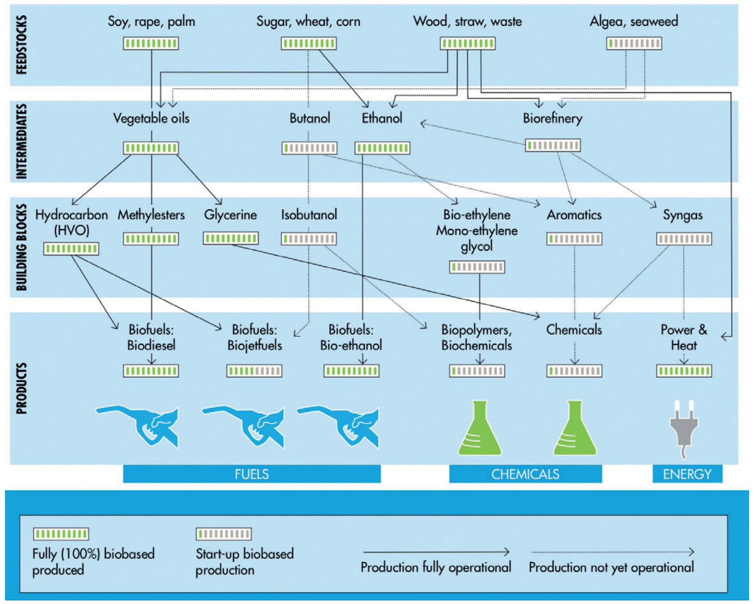



**Exhibit 28**: Bio-based industry in Rotterdam, *adapted from reference 42*

Bio-ethylene and bio-monoethylene glycol are currently not produced in the Rotterdam area, nor are any second and/or third generation technologies practised. There are several reasons for this. As a consequence, the production of bio-polymers and bio-chemicals has not taken off in the Rotterdam area, despite the fact that all the necessary infrastructure is available (Exhibit 30), including the new Maasvlakte 2.

Finally, Exhibit 31 shows a potential future integrated picture of biomass providers, technology providers, producers and end-users in the Rotterdam area, together forming the bio-based industry in Rotterdam.

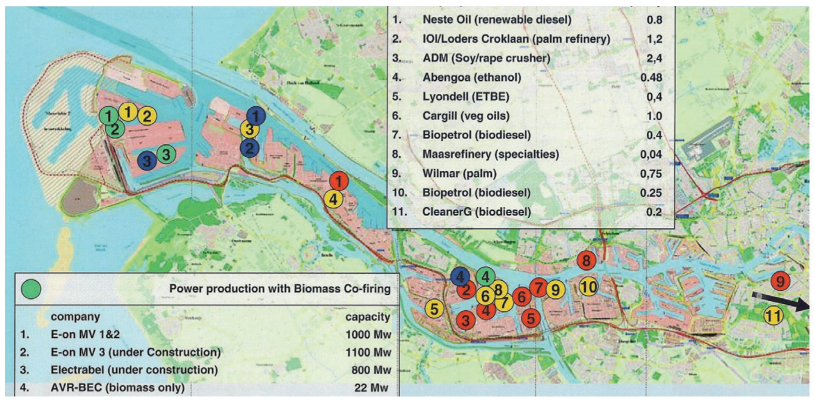



**Exhibit 29**: Bio based products in Rotterdam area, *adapted from reference 42*



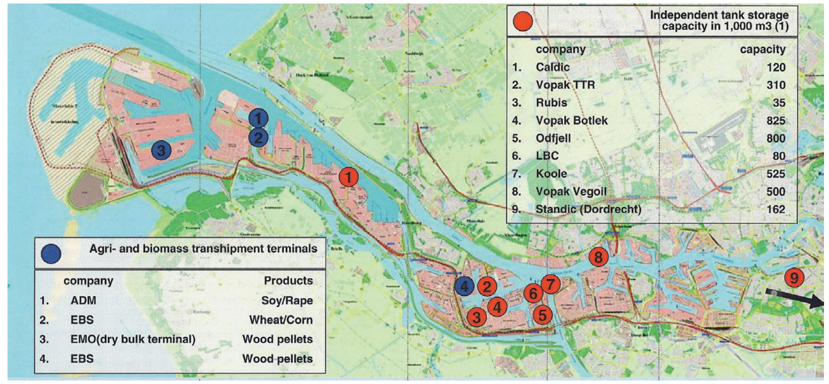



**Exhibit 30**: BioPort Rotterdam: feedstocks and intermediates, *adapted from reference 42*

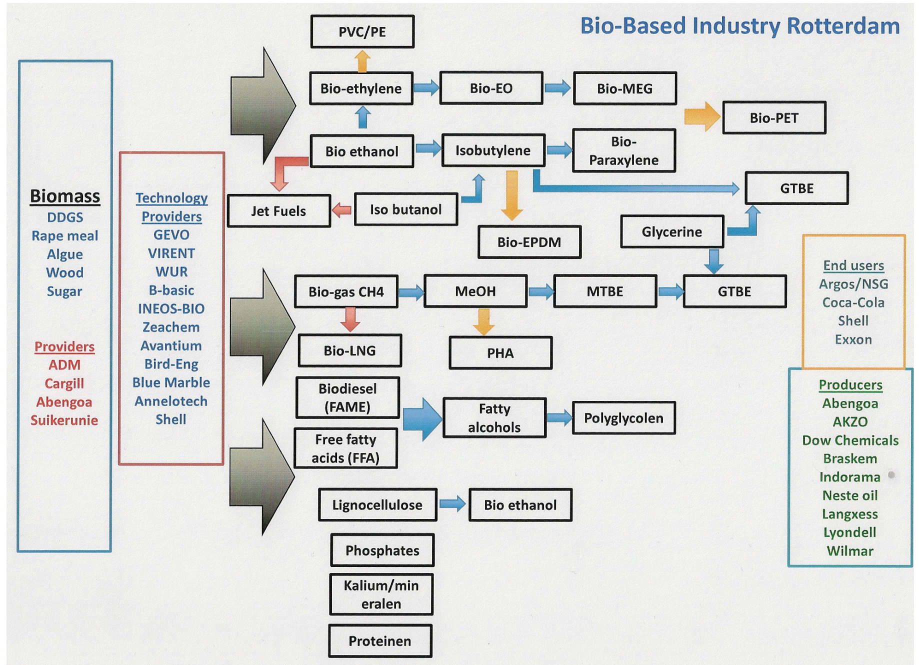



**Exhibit 31**: Bio-based industry in Rotterdam, *adapted from reference 43*

# 6. Bio-based Economy and Education

Many studies have concluded that the economy of the 21st century will be bio-based. During the transition from an oil-based economy to a bio-based economy, products and processes based on biological raw materials will replace those based on fossil fuels. Bio-refineries will use many types of biomass sources and produce a broad range of carbon-based products, including energy, fuels, chemicals, oils and many types of bio-materials.

Many technological challenges must be overcome for this vision of the bio-based economy to be realised. To address these challenges, skilled chemists and engineers will be required to work in cross-functional teams.

Does the current educational system anticipate the bio-based economy?

A survey[49] amongst students in the Netherlands in relation to the theme of the bio-based economy showed that young people are relatively unfamiliar with the term "bio-based economy", but that after having it explained to them there is a lot of interest in studying the subject. Employers estimate that 10,000 to 20,000 new, high-value positions will be needed in the bio-based economy in the Netherlands[47] in the next 20 years.

It is fair to say that the current education system is not sufficiently knowledgeable of and does not have sufficient expertise in the area of the bio-based economy. Courses with special relevance to bio-based industry need to be developed. Such courses should focus on topics relevant to the utilisation of diverse biological materials, improving technologies for the processing and production of sustainable energy and new functional molecules, the principles of green engineering and green chemistry.[44,48] Future employees educated to bachelor's degree level will also have to have a broad range of knowledge and hands-on experience of bio-process technologies. The current Chemical Engineering curriculum does not provide such knowledge and experience. The development of novel courses that provide laboratory experience in research techniques relevant to bioprocesses and bioprocessing should therefore be encouraged.

On 1 January 2012, the Centre for Bio-Based Economy (CBBE) was created with a subsidy of €5 million from the Ministry of Economic Affairs, Agriculture and Innovation. CBBE is an initiative of Wageningen University and various universities of applied sciences (CAH Dronten, AVANS, InHolland Delft, HAS Den Bosch, Hogeschool Arnhem en Nijmegen and Hogeschool Van Hall Larenstein Leeuwarden). The objective of CBBE is to develop training and education around the theme of the bio-based economy, with the aim of creating a workforce of well-educated professionals.

The CBBE will promote knowledge transfer between corporations and education/ knowledge institutes by means of:

- knowledge transfer and the development of training courses;
- strengthening applied research; and
- stimulating innovation projects.

It has the aim of becoming an intersection of education, applied research and innovation. The CBBE partners each have their own expertise in the bio-based chain, from bio-based products, production and bio-based technology, to feed stocks and raw materials (see Exhibit 32).

A possible future role for the Chemical Engineering faculty of Rotterdam Mainport University, RMU, is clearly complementary because of its strengths in chemical engineering and contacts with the chemical industry in the Rotterdam harbour area. Initial contacts with CBBE have been established and discussions on RMU joining CBBE are on-going.

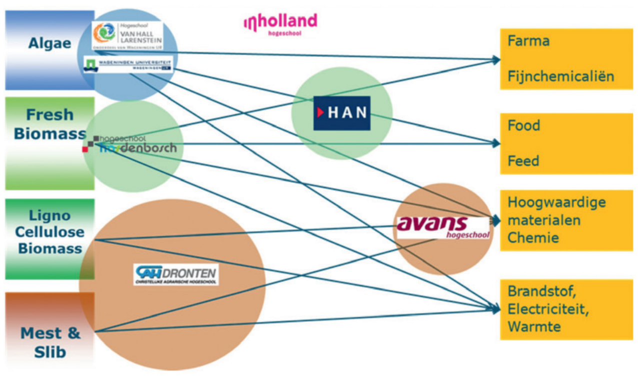



**Exhibit 32:** Positioning of institutes in CBBE, adapted from reference 43

While the discussions with CBBE continue, the Chemical Engineering faculty of RMU has embarked (for the time being) on a parallel path to adapt its curriculum. In a study conducted by Wageningen University,[46] it was concluded that dedicated bio-based education is not advisable. A better alternative is to integrate 'bio-based' components into the existing curriculum. This is also the philosophy of RMU. Graduates should also remain attractive future employees for the more traditional industries.

During a workshop in February 2013, two statements were posed:

*What minimum level of knowledge, competencies and behaviours should be included in the Chemical Engineering curriculum of Rotterdam Mainport University to allow future BSc engineers to contribute optimally to innovation, improvement and optimisation of the current technologies?*



and

*What knowledge, competencies and behaviours should Rotterdam Mainport University include in its Chemical Engineering curriculum in order for future BSc engineers to contribute successfully to corporate ambitions in relation to sustainability?*

The outcome of the discussion was translated into curriculum changes which will be introduced gradually, starting in the academic year 2013 – 2014 with a training module "Introduction to the Bio-Based Economy". More specialised and dedicated modules and electives will be developed. To qualify for 'Green Engineer' certification, the minor and the graduation work should be in the area of the bio-based economy. A Multi-Generational Plan for the period from 2012 to 2016 is shown in Exhibit 33. The objective is that in 2016 – 2017 the first 'Green Engineers' will graduate from Rotterdam Mainport University.

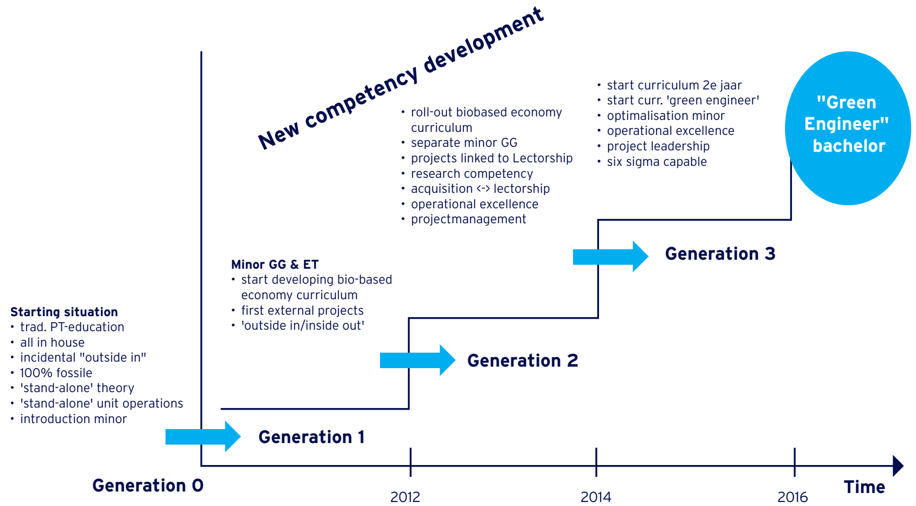



**Exhibit 33:** Multi-Generational Plan Chemical Engineering Education

*"No new 'green' education, but the incorporation of bio-based economy principles in existing curricula"*

**– Nelo Emerencia, VNCI**

## *The Twelve Principles Of Green Chemistry* [48]

1. **Prevention**
   It is better to prevent waste than to treat or clean up waste after it has been created.
2. **Atom Economy**
   Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Syntheses**
   Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals**
   Chemical products should be designed to affect their desired function while minimizing their toxicity.
5. **Safer Solvents and Auxiliaries**
   The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. **Design for Energy Efficiency**
   Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. **Use of Renewable Feedstocks**
   A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives**
   Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. **Catalysis**
   Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **Design for Degradation**
    Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. **Real-time analysis for Pollution Prevention**
    Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention**
    Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.



## *The Twelve Principles Of Green Engineering* [44]

1. **Inherent Rather Than Circumstantial**
   Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
2. **Prevention Instead of Treatment**
   It is better to prevent waste than to treat or clean up waste after it is formed.
3. **Design for Separation**
   Separation and purification operations should be designed to minimize energy consumption and materials use.
4. **Maximize Efficiency**
   Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5. **Output-Pulled Versus Input-Pushed**
   Products, processes, and systems should be “output pulled” rather than "input pushed" through the use of energy and materials.
6. **Conserve Complexity**
   Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7. **Durability Rather Than Immortality**
   Targeted durability, not immortality, should be a design goal.
8. **Meet Need, Minimize Excess**
   Design for unnecessary capacity or capability (e.g., “one size fits all”) solutions should be considered a design flaw.
9. **Minimize Material Diversity**
   Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10. **Integrate Material and Energy Flows**
    Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11. **Design for Commercial “Afterlife”**
    Products, processes, and systems should be designed for performance in a commercial “afterlife.”
12. **Renewable Rather Than Depleting**
    Material and energy inputs should be renewable rather than depleting.

## STATEMENT 8

**The incorporation of Green Chemistry and Green Engineering Principles in the Chemical Engineering curriculum will prepare graduates for the transition to a bio-based Economy in the Rotterdam area.**

# 7. Research Agenda 2013 - 2016

*"The art of being wise is the art of knowing what to overlook"*

**William James - American Philosopher 1842 - 1910**

As was already mentioned earlier, in contrast to coal or oil, biomass contains a wide array of different components that ought to be applied in a way that adds more value than merely being a source of energy (see also Exhibit 12). The separation of biomass and the refining of the various fractions is a challenge for the sustainable use of biomass. A number of techniques, some already more than a century old, have been revitalised and reinvented for modern commercial applications. Other techniques are barely out of the laboratory stage and involve state-of-the-art methods, such as genetic modification.

In the future it will be essential to combine biomass, processing techniques and end-products. No longer will biomass determine the end-product, but the desired end-product, or combination of end-products, will determine the type of biomass chosen and the processing technique. Developing robust processes that accommodate multiple feedstock streams is therefore essential.

Pyrolysis, torrefaction, fermentation and bio-refining are such processing techniques that need significant further research and development. Key technologies that need development are cost-effective refining (e.g. better recovery and purification technology for diluted aqueous solutions) and catalysis. As most of this type of research will need practical experimentation, significant equipment (and thus capital) resources will be needed. These resources are not available within the Rotterdam Mainport University/Hogeschool Rotterdam. The approach that Research Centre Mainport Innovation, RCMI, 'Innovation in the Process Industry' will take is to seek alliances and partnerships with corporations and institutes in the Rotterdam area and align its projects with corporate needs.

This approach will have advantages and disadvantages. The advantages are that, by definition, the research will be perfectly aligned with the needs in the Rotterdam area. Research will support education, and *vice versa*, as the research will be carried out through training, minor and/or graduation projects. A strong network with corporations and institutes in the Rotterdam area is essential. As such, this approach is perfectly aligned with that described in the strategic research policy of the Hogeschool Rotterdam.[50]

On the downside, it will be very difficult, but not impossible, to develop a specific area of expertise within RCMI, unless the right partners can be identified. It is possible to specify areas of focus. In the period from 2013 to 2016, our research will focus on *materials* from first generation biomass, and *chemicals/fuels* from second generation biomass (Exhibit 34). Research on bio-fuels from first generation biomass should be avoided because of the low added value of fuels as well as the longer-term acceptance of the use of first generation feed stocks for fuels ('food versus fuel' debate). Research on third generation biomass is too speculative and still too fundamental for RCMI to make an impact. However, it may fall within the scope of our activities from 2016 onwards, when the first scaling up of these technologies will (hopefully) take place. Cell 1 to 4 in Exhibit 34 indicates a relative priority, which is a compromise between the interests of RCMI and the needs of industry.

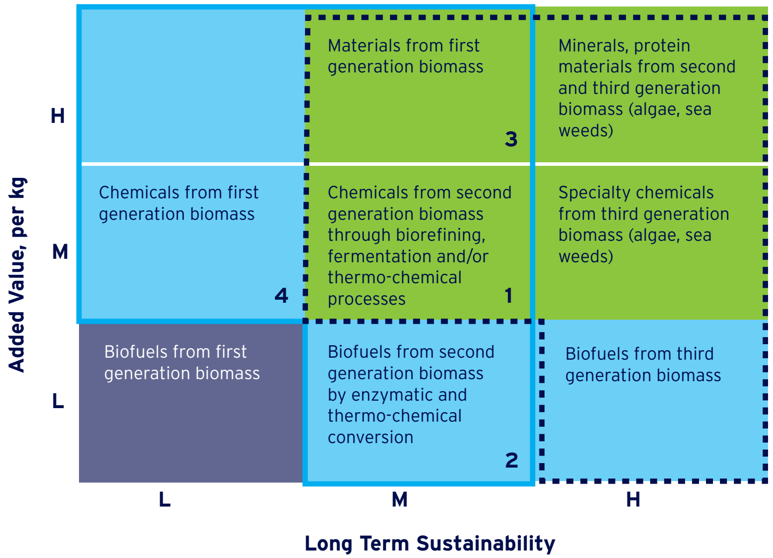



**Exhibit 34:** Priority focus areas of RCMI's projects, 2012 – 2016

Our specific interest concerning our future research agenda is in the area of thermochemical conversion processes for second generation biomass, and biomass pyrolysis in particular (#1 in Exhibit 34). Biomass fast pyrolysis is a thermal process during which the raw materials are heated rapidly to a temperature ranging from 450 to 500 °C in the absence of oxygen. Under these conditions, biomass is converted into organic compounds, vapours, non-condensable gases and liquid tar. The organic vapours are then condensed, thus producing the pyrolysis oil, or bio-oil. A wide range of biomass feedstocks can be used in the process. Pyrolysis oil may be used as a fuel for power production or as a raw material in the production of chemicals. Its physical form results in handling, storage and transportation characteristics that fit well with the current chemical infrastructure of the Rotterdam area. Its energy density (three to five times higher than that of biomass feedstock) and possible decentralised production in regions where biomass is readily available minimise costly logistical movements which partly eliminate the environmental advantages of



biomass feedstock. Pyrolysis oil can also be fractionated in various qualities of oil needed for further upgrading to chemicals, such as phenols and other aromatics. It is this area of bio-aromatics that has our specific research interest, because of the reasons mentioned in section 4.4.

Finally, Exhibit 35 shows the Multi-Generational Plan 2012 – 2016 for developing a project portfolio and for the integration of research with industry and education. From a more ad hoc approach to doing research in the period from 2010 to 2012, RCMI will start to develop a more coherent project portfolio. This project portfolio will generate opportunities for thesis work, publications and presentations in the period from 2014 onwards. In 2013 and 2014, the main emphasis will be on building a strong network within the Rotterdam area, building a strong project portfolio and exploring sources of external funding for our research.

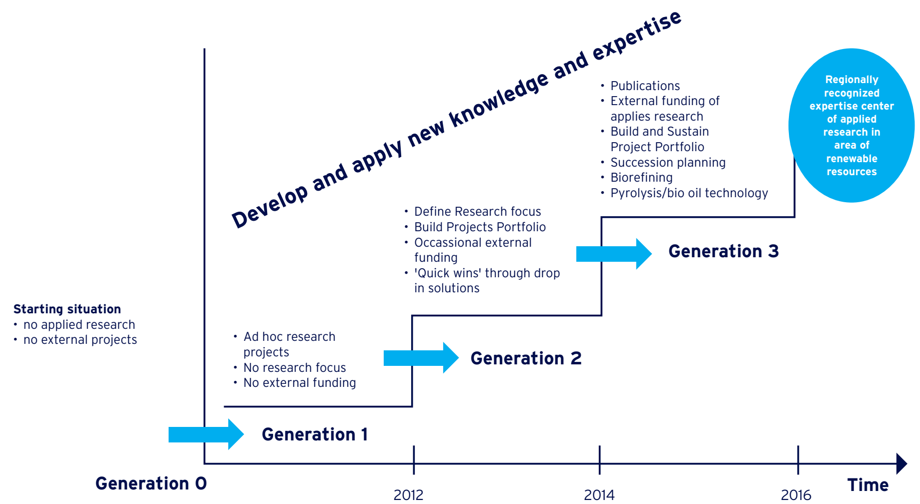



**Exhibit 35:** Multi-Generational Plan Research 2012 – 2016

## STATEMENT 9

**Thermochemical processes for the production of energy and chemicals from second generation biomass fit well with the infrastructure and needs in the Rotterdam Area.**

# 8. Summary

This document has perhaps left you feeling ambivalent, or has possibly even been cause for concern. Why go through all this trouble? Why should Research Centre Mainport Innovation even bother to address these issues?

These questions call to mind the 'change cycle' (Exhibit 36). The transition to a bio-based economy is not different from any other change. Consequently we, and mankind as a whole, will go through similar emotions: *uninformed optimism, informed pessimism, hopeful realism, informed optimism* and, finally, *acceptance*. *Public or private checkout* may also occur.

Today we are probably in the *informed pessimism* phase. New technologies need to be developed, costs are high, product/process economics are not competitive and investments are huge. Public checkout is taking place with companies scaling back their 'green' innovation budgets and investment plans, and focusing entirely on cheaper fossil feedstocks, also driven by the current economic climate, depressed product margins and profitability.[45]

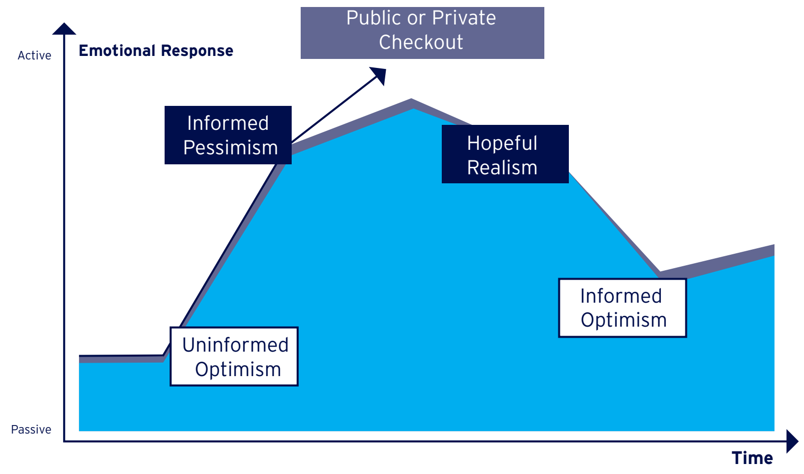



**Exhibit 36:** The Change Cycle

There is no denying that there has been (and still is) some hype around the bio-based economy. Expectations are high, media attention and policy push are significant – the peak of inflated expectation (Exhibit 37). The market, however, is not (yet) exerting a pull and corporations are taking a wait-and-see approach in anticipation of the emergence of dominant technologies. We are in a period of disillusion, where the interest, particularly from large multinational companies, wanes, also because of the high capital investments involved and lack of economic feasibility of many of the bio-based investments. In most cases, the oil price would need to be around $200 bbl., i.e. double today's price, for commodity chemical companies to become interested again.

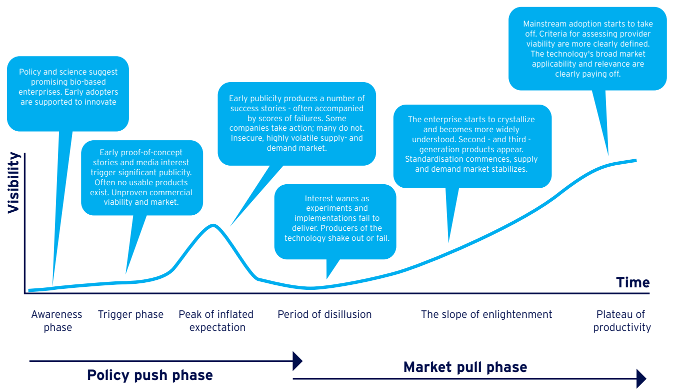



**Exhibit 37**: The hype cycle, adapted from Gartner Consulting 50

However, returning to the change model again, we should move to the stage of *Hopeful Realism* as soon as possible. Sustainability is not optional.

The rise of shale gas also provides opportunities, the most important of all being time. Because of the low(er) energy prices, the profitability of chemical companies will improve, freeing up more future innovation and funds for investment. In addition, many of the technologies are far from developed. Time will be needed for dominant technologies to emerge. After all, the development of major new technologies will take more than 10 years, and possibly even up to 50 years (Exhibit 38). As was mentioned earlier, because of the shift to shale gas as a feedstock for commodity chemicals, certain other chemicals, such as benzene, toluene and xylene, will become less readily available from fossil sources and will consequently increase in price. This provides an opportunity for the bio-based technologies to reach the break-even point much sooner.

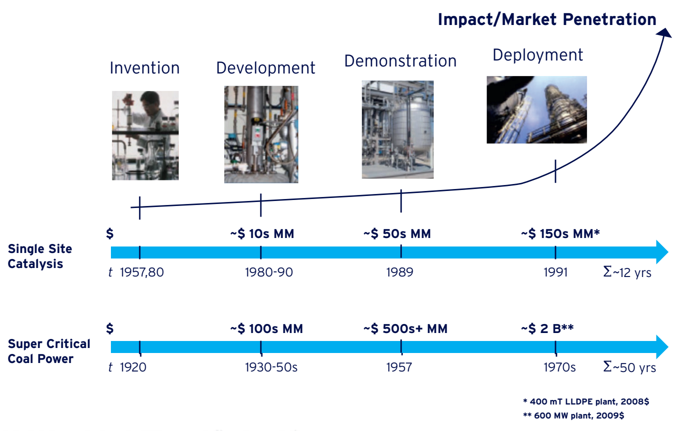



**Exhibit 38**: Technology impact/market penetration time, adapted from reference[25]



In conclusion, we are still at the beginning of a major transition, one that will take two or three generations to complete, possibly until the end of this century. Mankind will have no alternative other than to '*go back to the land*'. There will be setbacks, disappointments and failures. However, despite the shale-gas 'revolution', we should stay focused on the development of new, bio-based technologies. Innovation has, by definition, a long-term horizon and should not be subject to next quarter's financial results. In fact, shale gas may prove to be a blessing in disguise. It will buy us time to develop new technologies and improve profitability for companies to invest in innovation. Corporations, policymakers and institutions should stay the course towards a circular, bio-based economy, and not be distracted by 'blips' on the timeline of mankind, such as shale gas.

## STATEMENT 10

**The word "sustainable" is unsustainable.**

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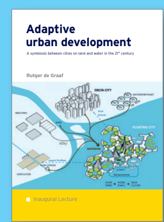


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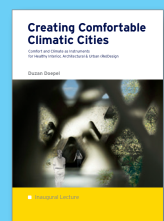


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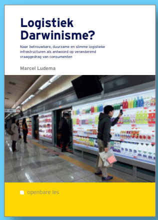


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