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TNO report

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Quick scan of the economical, technological and environmental aspects of biomass value chains

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Contents

1 Introduction

The work presented in this report is a result of the AERTOs project, an ERA-NET project of seven RTOs in Europe: Fraunhofer, CEA, SINTEF, SP, TNO, Tecnalia and VTT. The objective is to identify, design and implement “joint, long-term, sustainable cooperation activities between RTOs”. The purpose of this work is a bottom-up approach to develop and deploy joint activities towards a Bio-based Economy. The results of this report will deliver input for a more extensive paper about the position of the RTOs in Europe.

This report contains a quick scan of various biomass value chains that could emerge. The purpose is threefold:

- Benchmark various possible value chains against each other in terms of CO_2 emissions, energy requirements, and economic added value. This way, priorities can be set for the development of one chain over another.
- Provide a clear insight into the difficulties of organizing the value chain. Which sectors / companies should be involved and what is their incentive to be involved? Typically, organizing the chain requires a simultaneous decision in several sectors. This happens only if someone organizes the chain.
- Provide guidance for technology development by showing the bottlenecks in the value chain and by providing clear objectives for technology developments to eliminate these bottlenecks.

To achieve this, together with the AERTOs partners several bio-based chains were selected for further evaluation. Next, the technological, economical and environmental aspects of each step of the production chain were determined. By integrating this data over the full chain, the chains could be compared to each other in a consistent way. A sensitivity analysis then provided insight into the bottlenecks in the value chain.

This document contains an overview of the results and conclusions of this analysis for the chains of three bio-based products (involved partners shown between brackets):

- Production of itaconic acid from woody biomass (*TNO, SINTEF)*
- Production of ethanol from wheat straw (*TNO*)
- Production of omega-3 fatty acids from micro-algae (*TNO, Fraunhofer*)

Chapter 2 contains more information about the methodology used to assess the three chains. Chapter 3 contains a summary of the results and general conclusions. Chapters 4, 5 and 6 are detailed reports of the three chains.

2 Methodology

The analysis was completed in four parts: chain definition, data collection, technical and financial analysis, and a quick market evaluation. The other AERTOs partners were involved in the first two steps while TNO took the lead in the last two. Several departments of TNO were consulted for input on the reporting of each chain.

The first part, the chain definition, included determining the feedstock, process steps, and end product. The feedstock-to-product and general processing technology were chosen by a voting procedure between all the partners. The details of the process steps were then worked out with the partner submitting the chain with some limitations by the amount data available. The system boundaries were defined by TNO to include only the process itself. For example, the emissions and usage of the diesel fuel needed to harvest the feedstocks were included, but the values for the production of the diesel were not. The scale of the system was also not specified explicitly for this study, but instead determined by the available data. Economies of scale will be an important factor for some chains, but this was beyond the scope of this report.

For the data collection, industrial contacts and experimental results were consulted when available. Literature values were then used to complete the required set of data for each chain with as much detail as possible. The sources of the data were always cited clearly to ensure the transparency of the results. The values that were determined for each step of the chain were the energy requirements, CO_2 emissions, capital costs, operating costs, and yield. The market value of the bio-based product was also found, in some cases based on the price of the conventional fossil-based product the bio-based product would be most likely to replace. A full analysis for the conventional product was not carried out, but in every case the parameters most applicable to sustainability - energy requirements and CO_2 emissions-were found in literature.

The final values at the end of the chain for the costs, amount of product per year, required feedstock, and emissions were input into RETScreen International, an energy system analysis software. This allowed for definition of a production system, a cost breakdown, and specification of several financial parameters, including a sustainability credit for each unit of product produced. The risk and sensitivity analyses were also carried out with RETScreen.

Another part of analysis required to produce the report for each chain was a market evaluation to determine the potential market size for the bio-based product based on the market for the conventional fossil-based product. This allowed for an estimation of what the limiting factor is most likely to be, feedstock availability or market size, and gave insight into the overall value and the possible difficulties that could arise with large scale implementation of the bio-based chain.

3 Summary

Below is a short summary of the analysis of each chain followed by the conclusion that can be based on the analysis.

3.1 Production of itaconic acid from woody biomass

Itaconic acid has been identified as one of the most promising bio-based chemicals with the potential to replace fossil-based acrylic acid and its derivatives. Several production chains are possible, but the specific chain analyzed in the study considered a pine wood feedstock, steam explosion pre-treatment, hydrolysis and neutral pH fermentation, dewatering, and crystallization. A refinery based on this technology with a capacity of 0.3 ton itaconic acid/yr resulted, however, in a negative business case.
A sensitivity analysis was performed on the parameters with the most impact on the economics-OPEX, CAPEX, and process yield, in that order-and showed that the business case would just become positive with a 20% reduction in OPEX, a 60% reduction in CAPEX, or a 20% increase in yield. The fermentation and pre-treatment steps were the major contributors to the CAPEX while the post-processing was by far the highest for the OPEX. Several other options (like different pre-treatment technologies or low pH fermentation, which obviates the need for waste salt production) exist for these steps, but the evaluation of those options was not part of the scope of this project.

3.2 Production of ethanol from wheat straw

The production of ethanol from bio-based sources is a well-known technology, but utilizing ligno-cellulosic 2nd generation feedstocks is still in development. The analysis was carried out on the chain converting wheat straw, an agricultural waste product, through mild acid pre-treatment, simultaneous saccharification (hydrolysis) and fermentation, distillation, and dehydration to yield fuel grade (99.6%) ethanol. For a refinery with a capacity of 150 ton ethanol/yr, an IRR of 26% was calculated.
Using agricultural waste as the feedstock, especially if it can be collected at the same time as the primary agricultural product, and producing the process electricity by combustion of the process waste dramatically improve the process sustainability relative to the conventional fossil-based process. Feedstock supply/price could be an issue with large scale implementation of the value chain and increased demand, but the other factors-market price, operating costs, and yield-have more impact on the economics and are expected to improve.

3.3 Production of omega-3 fatty acids from micro-algae

The evaluated production chain of omega-3 fatty acid-rich oil from algae consisted of the cultivation of algae in naturally illuminated tubular bio-reactors, harvesting by centrifugation and extraction by supercritical CO_2 extraction. For a 1 ha system yielding 18.5 tons oil per year, an IRR of 25% was calculated. In comparison to the conventional way of producing omega-3 fatty acids, this way is also more sustainable.
As the market price of omega-3 fatty acids is quite high (€40/kg), this result is not surprising. A sensitivity analysis showed a minimum required market price of €26/kg for products of this system. Main critical factors for improving the business case towards lower value products were found to be increasing culture densities or decreased pumping requirements by improved reactor design.

3.4 Conclusions

Table 1 contains a quantitative comparison of the three evaluated chains.

Table 1 Quantitative comparison of different chains assuming 10 year project life in each case.

	Itaconic acid from woody biomass	**Ethanol from wheat straw**	**Omega-3 fatty acids from algae**
Production size	2.4 kton/yr	150 kton/yr	18.5 ton/yr
Feedstock input size	21.9 kton/yr	688 kton/yr	41 dw ton/yr
Feedstock cost	46 EUR/ton	38.5 EUR/ton	-
CAPEX	12.9 MEUR (538 EUR/ton)	79.8 MEUR (53.2 EUR/ton)	1.4 MEUR (7370 EUR/ton)
OPEX	2.71 kEUR/ton	0.550 kEUR/ton	16.3 kEUR/ton
Emitted CO_2	5826 kg/ton	2045 kg/ton	1368 kg/ton
Energy requirements	13.8 MWh/ton	2.39 MWh/ton	13,900 MWh/ton
Market size estimate	0.015 Mton	82.7 Mton	71.4 Mton
Market value	3.25 EUR/kg	0.90 EUR/kg	40 EUR/kg
Benchmark required energy	43.7 GJ/ton	58 GJ/ton	1340 GJ/ton
Benchmark required CO_2	1670 kg/ton	1990 kg/ton	85,700 kg/ton
Internal Rate of Return	-	26%	25%
10-year NPV	-10 MEUR	102 MEUR	1.7 MEUR

For each specific chain the following conclusions can be drawn.

Itaconic acid from woody biomass
- Economically not feasible due to relatively high production costs
- Possible solutions are
  - taking the conversion of hemicellulose also into account, since this can improve the feedstock utilization efficiency with 25%
  - Lignin combustion to replace the need for fossil fuels for pretreatment
  - Applying simultaneous saccharification and fermentation
  - Low pH fermentation process can reduce the cost for down-stream processing and decreases environmental impact

Ethanol from wheat straw
- Economically feasible
- Feedstock supply could be an issue for large scale application

Omega-3 fatty acids from algae
- High-value chemicals (>20 EUR/kg) production from evaluated system is feasible
- Production of lower value chemicals requires a strong reduction of operational costs (mainly caused by cultivation of algae)

The methodology used to perform a technical and market analysis of emerging bio-based production chains gives insight into the economic prospects, risks, and sustainability of the individual value chains with respect to conventional processes. The environmental, technical and economic feasibility of bio-based chains is not obvious and many factors play a role. An accurate comparison/benchmarking of different chains is challenging and requires a systematic approach in which chains are analyzed. This approach should consist of
- a consistent manner of defining the production chain with logical inputs and outputs and a well defined system boundary;
- clever clusters of variables that can easily be compared across different production chains;
- a clear sensitivity analysis of the main critical parameters;
- a concise way in which results are reported/presented.

TNO is developing such an approach to be able to (i) classify contemporary and novel bio-based production chains, (ii) identify bottlenecks for large-scale realization and (iii) analyze possible breakthrough scenario's to eventually implement bio-based chains successfully. However, the methodology used here is a very effective way for providing insight into the critical factors and gives directions for future bio-based developments.

4 Production of itaconic acid from woody biomass

4.1 Management summary

Itaconic acid has been identified as one of the most promising bio-based chemicals with the potential to replace fossil-based acrylic acid and its derivatives. Several production chains are possible, but the specific chain analyzed in the study considered a pine wood feedstock, steam explosion pre-treatment, hydrolysis and fermentation, dewatering, and crystallization. The current market price of itaconic acid was used in the calculations even though it was about twice as much as that for acrylic acid. The price of itaconic acid would have to be reduced or a premium would have to be paid for there to be large market opportunities. It was also realized that the choice of feedstock and pre-treatment has a large impact on the outcome of the results. The specifics of the chain and the data were provided by SINTEF based on in-house knowledge and so a thorough assessment of different options was not initiated. It is thought that other chains, especially with newly improved processing steps would give significantly improved results than those found for the chain described here.

The results of the technical analysis showed high capital and operating costs at 12.9 M€ and 6.47 M€/yr, respectively, based on a feedstock input of 2.5 ton/hr, yielding 276 kg itaconic acid/yr. The fermentation and pre-treatment steps were the major contributors to the CAPEX while the post-processing was by far the highest for the OPEX. The energy requirements were very high at 33 GWh/yr, or 434 GJ/kg, mostly due to the fermentation and post-processing. The same two steps also contributed the most to the CO_2 emissions. The emissions from the fermentation reactions accounted for 37% of the total emissions at 14 Mton/yr, or 5826 kg/ton, but given that the CO_2 from the fermentation has a much lower environmental impact than the fossil-based emissions, they were not considered in assessing the sustainability of the chain. Still, comparing this chain to the production of acrylic acid, requiring 43.7 GJ/ton energy and emitting 1670 kg CO_2/ton, it was clear that substantial improvements are needed to realize benefits from implementing the bio-based chain. A quick scan life cycle assessment was also completed and validated these results.

At the same time, the economics of the chain were also not positive. The high costs resulted in an NPV of -10 M€ after 10 years. It was found that a 14% credit or premium (€0.44/kg) resulted in a positive business case. A sensitivity analysis was performed on the other parameters with the most impact on the economics-OPEX, CAPEX, and process yield, in that order — and showed that the business case would just become positive with a 20% reduction in OPEX, a 60% reduction in CAPEX, or a 20% increase in yield. It is probable that the OPEX and yield will improve with continuing research and more optimal production chains, but the CAPEX is likely to require significant investments to promote the value chain. For itaconic acid to become competitive with acrylic acid at half the price, the required improvements would be even more dramatic.

The general conclusions of the analysis were that significant improvements are needed to make this value chain economically attractive and more sustainable than the fossil-based process. Utilizing forestry waste or producing the process electricity through combustion of the process waste would be beneficial for both the economics and sustainability of the chain. Other technologies and feedstocks that are currently in development for the production of itaconic acid need to be investigated before the chain is implemented to determine the optimal feedstock and pre-treatment combination, and possibly show greatly improved results.

4.2 Chain description

This chain is focused on the production of (bio-)itaconic acid from pine wood through a fermentation chain. Itaconic acid has been identified as one of the top 12 value added chemicals from biomass by the United Stated Department of Energy with applications in several industries, especially paper and coatings.[1] The potential of itaconic acid would be the replacement of petroleum-produced acrylic acid and its derivatives in the production of plastics, paints, adhesives, detergents, and several other industrial materials.

The steps of the chain that have been evaluated in this study are the following:
- *Collection of biomass*. The pine wood must be logged (cut down, bundled, etc.) and transported by truck to the processing plant. A collection area at a distance of 80 km from the plant is assumed.
- *Pre-treatment*. Pine wood is first shredded to chips, then pre-treated by a steam explosion process (2-5 minute exposure to steam at 15-30 bar pressure) to make the cellulose fibers accessible for enzymatic processing.
- *Hydrolysis*. Enzymatic hydrolysis was considered here as a low cost, low energy option to convert the cellulose and/or glucomannan to glucose. The lignin was considered to still be present as insoluble lignin.
- *Fermentation*. The fermentation process was taken to occur in three separate fermentors as batch processes, with different periodic starting times, and each requiring 96 hours fermentation time. The use of the waste cell mass was not considered here.
- *Post-processing*. The itaconic acid was obtained from the fermentation batch through several consecutive steps including an ion exchange process, evaporation, crystallization, and centrifugation. No drying of the itaconic acid crystals was considered in either the investment or operation costs. In addition, the use of the waste (microorganisms, lignin and pentoses) as by-products was not considered.

The microbiological production of itaconic acid was patented in 1993[2] with subsequent patents involving various fermentation organisms issued as recently as January 2009. The main development of the chain presented here is the method of obtaining the glucose. Conventionally, glucose is obtained from natural starches from first-generation biomass sources that compete with the food supply (potatoes, cereals, and corn).

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[1] http://www.icis.com/blogs/green-chemicals/2009/10/what-is-itaconic-acid.html, accessed 20 October 2010.

[2] "Microbiological Production of Itaconic Acid," *United States, assignee*. Patent 5231016. 27 July 1993.

The pine wood feedstock discussed here is a second-generation feedstock and requires the extra pre-treatment step. Several options are available for the pre-treatment of the pine wood, including mild acid and mild alkaline processes. The steam explosion process was chosen for this analysis as it is a low cost, rapid process with little or no use of chemicals and a high wood to liquid ratio. Data was also available
in-house at SINTEF for this process.

The final product of the chain is only the itaconic acid. Its use and any further processing required to result in consumer products will not be discussed. Any logistical requirements for the storage and transport of the final product are also not considered.

4.3 Conventional process

The main use of itaconic acid would be as a replacement for acrylic acid, a chemical currently produced from fossil fuels. A full detailed analysis has not been done here, but cumulative values over the entire production chain for acrylic acid were found in the literature.[3] The available relevant parameters are:

- Energy demand = 43.7 GJ/ton
- CO_2 emissions = 1670 kg/ton

The costs of the system are not available, but given the long-term establishment and optimization of the petroleum industry, a large percentage of both the capital and operating costs are expected to be shared over several products. The contract sales price of acrylic acid is currently 1.83-1.95 €/kg[4] and appear to be highly sensitive to market trends and oil prices, almost doubling from about 1.00 €/kg in 2003.

4.4 Potential of value chain

4.4.1 Market

The market for itaconic acid in 2006 was approximately 15 kton/year, mostly limited by the high production costs.[5] With a reduction in price, currently 3.25 €/kg, the market has the potential to expand and compete with acrylic and methacrylic acid, with a much larger demand of 700 kton/year, but also much lower sales prices of about 1.89 €/kg. Another possible market would be in pressure-sensitive adhesives with a demand of 140 kton/year and market price of 3.00 to 6.00 €/kg (prices in 2003).[6]

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[3] M. Patel, "Cumulative energy demand (CED) and cumulative CO_2 emissions for products of the organic chemical industry," *Energy,* **28** (2003).
[4] "Acrylic Acid Prices and Pricing Information," http://www.icis.com/v2/chemicals/9074869/acrylic-acid/pricing.html, accessed 29 October 2010.
[5] Colin Ratledge and Bjørn Kristiansen, Basic Biotechnology, Cambridge University Press, 2006.
[6] "Biobased products: Itaconic Acid," *Wisconsin Biorefining Development Initiative,* http://www.biorefine.org/prod/ita.pdf.

The key technical barrier to further development of the itaconic acid process is the difficulty with its polymerization. If this were overcome, as is the claim by one company, Itaconix, poly-itaconic acid could be an attractive replacement for petroleum-based poly-acrylic acid. A range of applications-including superabsorbents, anti-scaling agents, detergents, dispersants, and plastics — would be possible with a global market of 1.65 Mton/year.[7]

Given the current high production costs, an expansion into petroleum-based markets is unlikely to occur in the near future. However, given improvements in bio-based technologies and governmental incentives to promote sustainable products, some increase in market share is expected occur in the medium-term (5-10 years) future. Using a conservative estimate of a 50% increase, market of 22.5 kton/year is taken as the expected market for itaconic acid in this report.

4.4.2 *Feedstock availability*

The feedstock for this value chain is pine wood and is widely available throughout Europe and globally, with the exploitable forest land in the EU15 totaling 92 Mha.[8] The annual growing capacity varies widely among regions from 50 m^3/ha in Spain to 310 m^3/ha in Austria, but assuming an annual average of 180 m^3/ha and a density of 0.5 ton/m^3, the total capacity for growing various types of wood in Europe is more than 8300 Mton/yr. Assuming 10% of this is available for pine wood feedstock, and of this 1% is available for itaconic acid production, the availability is still 8.3 Mton/year. From the calculations in this study, the annual production of itaconic acid from 8.3 Mton pine wood is about 0.92 Mton, almost 2 orders of magnitude greater than the current global market of 15 kton. The availability of feedstock is therefore not seen to be the limiting factor in this chain as long as production costs remain high.

The estimates for the availability of pine wood for the production of itaconic acid are very conservative. Several other types of wood may also be used (spruce, birch, aspen, etc.) along with various non-wood sources of lignocellulosic biomass (corn stover, wheat straw, etc.). In the United States, the available feedstock from forestry and agricultural residues alone is estimated at 240 Mton/year.[9] Given a complete shift in the market away from acrylic acid to sustainable itaconic acid and then with a market of 1.65 Mton/year (assuming the ability to polymerize itaconic acid is developed fully), the required global feedstock demand would be 14.9 Mton/year. This value is well below the global availability of feedstock given both the values from Europe and the United States and the flexibility in sources of lignocellulosic biomass. Other factors will also need to be considered, such as market trends and competition from other bio-based processes, but for the purposes of this report, the availability of feedstock, even with the maximum market share, is not seen to be the main barrier to this value chain.

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[7] Above n 1.
[8] Ericsson K. and L.J. Nilsson, *Biomass and Bioenergy,* **30** (2006).
[9] "Industrial Bioproducts: Today and Tomorrow," *U.S. Department of Energy, Office of Energy, Efficiency, and Renewable Energy,* March 2004.

4.5 Technical analysis

Several factors were evaluated for comparing the different chains and individual chain steps: capital investments (CAPEX), operating costs (OPEX), CO_2 emissions (not including equivalents for other emissions such as NO_X or CH_4), and energy requirements. The values from each successive step of the chain were cumulated with the final values, then used as input into the system analysis software RETScreen for the financial analysis. Figure 1 shows the results for each of the different parameters with the relative contribution from each step in the chain. The calculations were based on a feedstock supply of 2500 kg/hr, or 21.9 kton/yr. The resulting production of itaconic acid was found to be 276 kg/hr or 2.42 kton/yr. More detailed descriptions of the calculations are given in the following subsections along with an explanation of the other values used for input into RETScreen.

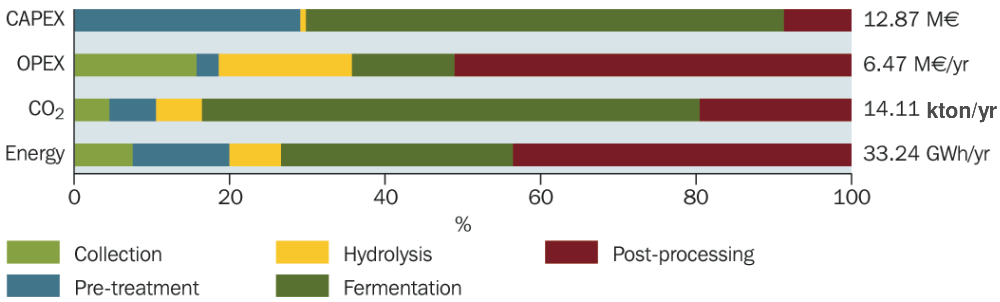


Figure 1 Relative cumulative values of the evaluated factors — CAPEX, OPEX, CO_2 emissions, and energy requirements — over each of the steps of the chain. The final values at the end of the chain are also shown.

4.5.1 Costs

The break down of both CAPEX and OPEX (including the feedstock cost) are given in Table 2 with a short description of what was considered for each value. The cost of the electricity required in each step is included in the values given here using the European average electricity price of 0.0809 €/kWh. More detailed data was not available or was not provided by the companies that were contacted in obtaining the data, but it is thought that the most important contributions to the costs are accounted for. Calculating costs for labor, start-up, and water treatment are improvements that can be made in future analyses.

Table 2 Data obtained for the CAPEX and OPEX of each step.

Process step	CAPEX (M€)	OPEX (M€/yr)	Description
Biomass collection	0	1.03	Cutting, bundling, and transport; assuming 80 km transport distance and pre-existing equipment
Pre-treatment	3.75	0.18	Shredding and steam-explosion equipment
Hydrolysis	0.08	1.11	Hydrolysis tank and enzymes
Fermentation	7.91	0.85	3 fermentors, heat exchanger for sterilization, and fermentation medium
Post-processing	1.13	3.30	Evaporator, centrifuge, crystallization, and required chemicals (NaOH, HCl, resin)

4.5.2 *Energy requirements and CO_2 emissions*

The energy requirements for the chain included diesel fuel usage, steam generation, and electricity. The level of detail of the data allowed for the calculation of the energy usage contribution to the total CO_2 emissions based on the different emissions factors for each type of energy. Other emissions factors, such as NO_X and CH_4, were not considered here. The associated CO_2 emissions factors were the following:

- diesel fuel = 3.16 kg CO_2/kg fuel
- steam generation = 184 kg CO_2/MWh
- electricity generation = 387 kg CO_2/MWh

The value for the CO_2 emissions for electricity production used in the calculations was the average value for OECD Europe for 1999-2002, found to be 387 kg CO_2/MWh electricity.[10] Due to the higher conversion efficiency of fuel to steam, the emissions are much lower. This difference was calculated using the same ratio of steam to electricity emissions (0.48) as used for the calculation of the acrylic acid benchmark chain. For the purposes of this report, this calculation and the absence of considering any heat integration was deemed sufficient. The breakdown of the types of energy required for each step is given in Table 3.

Table 3 Breakdown of energy requirements and CO_2 emissions for each step.

Process step	**Fuel (MWh/yr)**	**Steam (MWh/yr)**	**Electricity (MWh/yr)**	**CO_2 from energy consumption (ton/yr)**	**Total CO_2 (ton/yr)**
Biomass collection	2496	0	0	632.1	632.1
Pre-treatment	0	3807	361.4	841.0	841.0
Hydrolysis	0	0	2190	847.5	847.5
Fermentation	0	2.575	9932	3844	9039
Post-processing	0	14016	438	2751	2751
Total	**2496**	**17825**	**12921**	**8916**	**14110**
Non-fossil based emissions (ton/yr)					**5195**
Fossil-based electricity production emissions (ton/yr)					**8284**
Fossil-based fuel usage emissions (ton/yr)					**632.1**

The total CO_2 emissions for this chain were calculated to be 5826 kg CO_2/ton itaconic acid produced. This value included the emissions from the logging equipment used to collect the pine wood feedstock, the emissions directly from the fermentation step (those from the other steps were assumed to be negligible), and the emissions for the energy requirements of each step, as described above. It should be noted that no carbon uptake due to the growth of the feedstock was considered here. The total values for each step are also given in Table 3.

[10] "Voluntary reporting of greenhouse gases," *U.S. Department of Energy, Energy Information Administration,* October 2007.

4.5.3 *Benchmarking*

Comparing the final value of 5826 kg/ton to that for acrylic acid, 1670 kg/ton, there at first there seems to be no benefit at all from implementing the bio-based chain for itaconic acid. However, as shown in the last three rows of Table 3, the emissions should be divided into three different categories—non-fossil fuel based (from the fermentation step), fossil-based electricity production (from steam and electricity generation), and fossil-based fuel usage (from the logging equipment). The non-fossil based CO_2, accounting for 37% of the total emissions, is much cleaner than the fossil-based emissions and is produced at one closed point source (the fermentors). It should be feasible to capture the CO_2 given a tax on carbon or a value-adding use of the CO_2. Not including these emissions in the comparison with the acrylic acid benchmark gives a value of 3681 kg CO_2/ton itaconic acid.

This value is still significantly higher than the emissions for acrylic acid production, but other factors must still be considered. Given heat integration to reduce the energy requirements for steam generation and clean sources of electricity (solar, wind, nuclear, etc.), only the fuel for the logging equipment must be fossil-based (with today's technology) with emissions of only 261 kg CO_2/ton itaconic acid. On the other hand, acrylic acid is a derivative of products from the refining of crude oil and so is not able to be produced with much lower emissions, thus making the itaconic acid chain much more feasible for sustainable production.

RETScreen programming

The final values from the step-wise analysis of the itaconic acid chain were used as inputs into the system financial analysis, performed in the RETScreen software. The other financial parameters needed in the analysis were based on common values and the European average inflation rate, shown in Table 4.

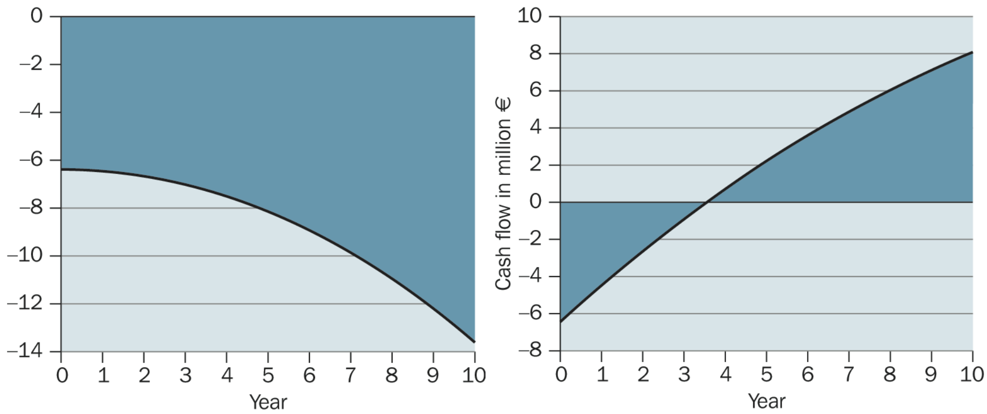
Table 4 Financial parameters used in RETScreen.

Parameter	Value	Parameter	Value
Fuel cost escalation rate	3.5 %	Debt ratio (% financed by companies)	50 %
Inflation rate	1.8 %	Debt interest rate	5.0 %
Discount rate	10 %	Debt term	10 years
Project life	10 years	Production credit escalation rate	1.8 %

The ability to specify a "production credit" is a feature of RETScreen that allows for a policy incentive or premium to be specified for sustainable products on a €/kg basis. The production credit escalation rate can then be specified to describe how the credit amount changes in subsequent years, either increasing or decreasing. In this analysis, a value of 1.8% was chosen to match the inflation rate and effectively have no change in the credit impact over time.

Although step-wise, the itaconic acid chain looks plausible, the final economics for the entire chain are not positive. Due to the high operating costs and energy requirements shown in Figure 1 (6.47 M€/yr and 33 GWh/yr, respectively), the sale price of the itaconic acid, currently at €3.25/kg, is not high enough to result in a positive business with no incentives or premiums offered. This is shown in part (a) of Figure 2 as the cumulative cash flow versus time.

Implementing a production credit for the sustainable production of chemicals would offer an incentive for companies to be involved in this value chain. The criteria for such an incentive would need to be specified by governmental bodies and could include processes that utilize sustainable carbon sources or renewable energy, for example. Part (b) of Figure 2 gives the results when a premium of 25% (a credit of 0.80 €/kg product) is applied and shows the break even point at about 42 months with a positive cash flow after 3.5 years. However, with a total investment from the government to support such a credit, equalling 19.2 M€ over 10 years for the payout of the production credit, this is not a practical solution, especially on a large scale. Other investments must be made to improve the technology or lower the costs. It should be noted that given the increase in CO_2 emissions for this chain compared to the acrylic acid chain discussed above, GHG emission taxes or credits for carbon trading were not considered in this analysis.



(a) **(b)**

Figure 2 Cumulative cash flow over the first 10 years of the project **(a)** with no credit for using biomass to produce itaconic acid and **(b)** with a 25% premium.

4.6 Sensitivity and risk analysis

A sensitivity and risk analysis was carried out to further investigate the most important factors in the economics of the value chain. The analysis was carried out on the net present value (NPV) of the chain as the best indicator of the financial feasibility of the chain. The financial parameters, costs, and production credit were allowed to vary over a wide range of ±100% to allow for effects of policies and incentives not present in conventional industries. Of particular interest for this value chain are the feedstock cost, itaconic acid price, and process yield.

Shown in Figure 3 is the impact graph giving the relative contributions of the variability in each key parameter to the outcome of the NPV. The axis at the bottom of the graph does not have any units, but rather presents a relative indication of the strength of the contribution of each parameter. The longer the horizontal bar for a given input parameter, the greater the impact of that parameter on the change in the NPV. The direction of each bar (positive or negative) indicates the relationship between the parameter and the NPV.

A positive relationship, for example with the price of itaconic acid, means that the NPV will increase with an increase in the parameter.

The results show that the most significant parameter in the outcome of the NPV is the price of itaconic acid, followed by the operating costs (not including the feedstock cost), capital costs, production credit rate (or premium), and feedstock cost, in that order. The effect of the process yield was not analyzed here directly, but is shown in Figure 4. The operating and feedstock costs and the price of itaconic acid are market driven, so that they are not so easily influenced with the implementation of policies. However, the capital costs can be more easily affected with policies in the form of grants, and its third position on the impact chart shows that such incentives may be a good way to promote this value chain. The production rate credit has a significant impact on the NPV and could be implemented directly, for example, with a policy as a set credit amount per amount of itaconic acid produced sustainably.

In terms of performing the analysis of a system, the larger bars also indicate which parameters should be studied in the most detail to ensure a high accuracy of the results. For example, an error of 10% in the value for the operating costs will have a much greater impact on the accuracy of the final result for the NPV than an error of 10% in the capital investments.

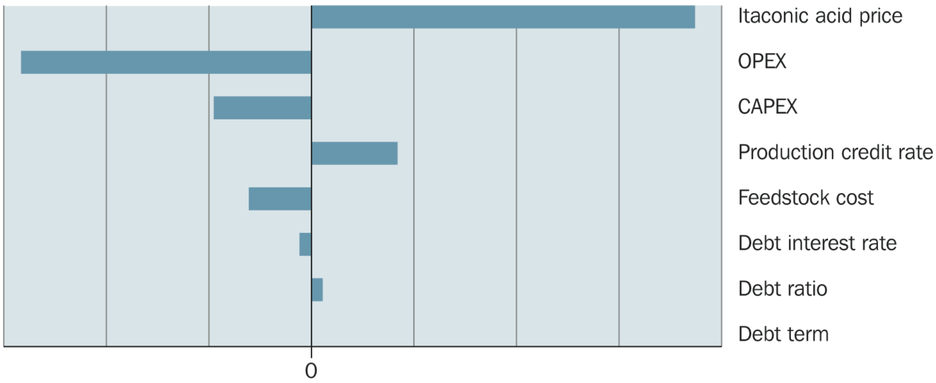


Figure 3 Impact graph showing the relative contribution of the variability in each key parameter to the outcome of the NPV. The axis at the bottom of the graph does not have any units, but rather presents a relative indication of the strength of the contribution of each parameter. The direction of each bar (positive or negative) indicates the relationship between the parameter and the NPV.

To look more closely at the importance of the key parameters in Figure 3, sensitivity analyses were performed on the calculation of the NPV, as shown in the contour plots in Figure 4, where the values indicate the NPV in million €, the green shades indicate a positive NPV, and the yellow to red shades indicate a negative NPV. As the production credit is most likely the best implementation of a policy to promote this chain, it was used in each analysis to show the level of credit needed given a certain change in the other indicated parameter. The starting value (0% change) for the production credit was set at 0.40 €/kg itaconic acid so that a -100% change indicates no credit and a +100% change equals the 0.80 €/kg credit that resulted in the example positive business case in Figure 2(b).

The starting values for the other parameters were those from the results of the step-wise analysis of the full chain:

- Feedstock cost = 46 €/ton
- CAPEX = 12.87 M€
- OPEX excluding feedstock cost = 5.45 M€/yr

The process yield was also analyzed by keeping the supply of feedstock constant at the 2500 kg/hr value. The output of itaconic acid, calculated to be 110.6 kg itaconic acid/ton feedstock in the step-wise analysis, was then varied between 0 and a 100% increase to 221.2 kg/ton. This affected both the income from the sale of the itaconic acid and the income from the sustainable production credit. The result, shown in part (d) of Figure 4 showed a very high sensitivity of the NPV to the process yield. More specific conclusions resulting from the sensitivity analysis are given below.

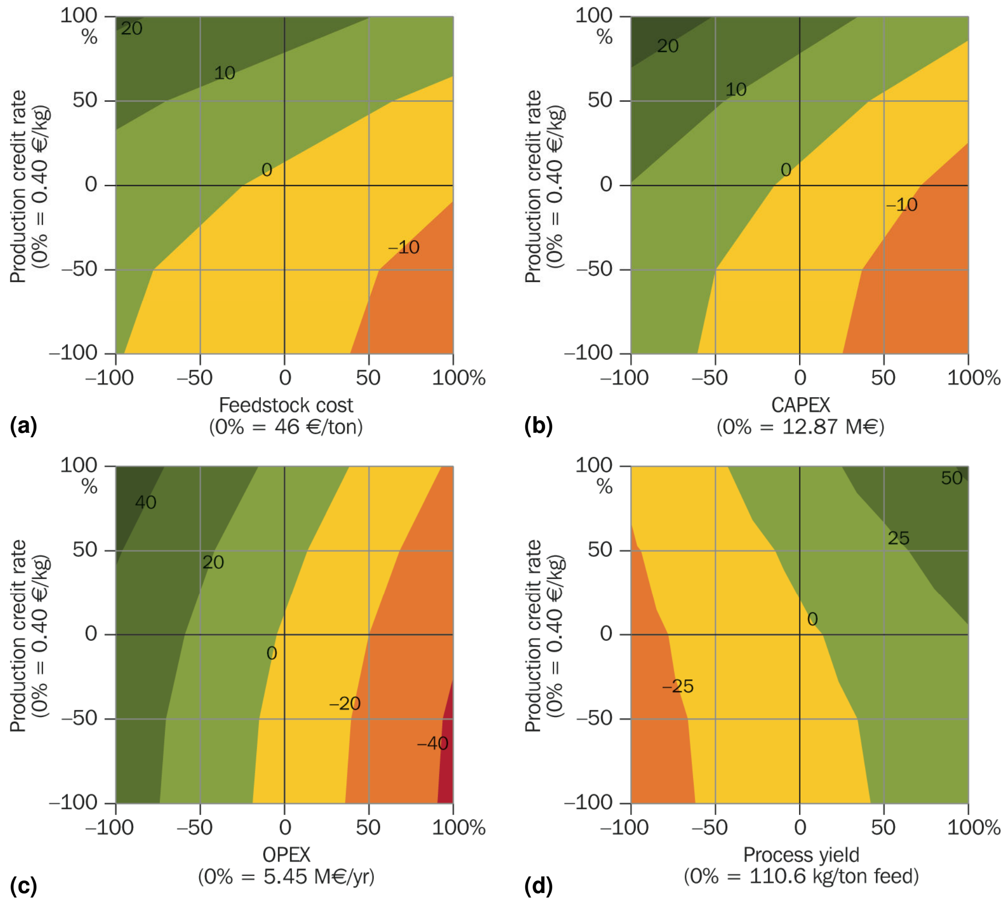


Figure 4 Sensitivity of the NPV to the top key parameters.

The results clearly show the relationships between the NPV and the feedstock cost, CAPEX, and itaconic acid price as expected from the impact chart of Figure 3. Particular features to note that are not seen from Figure 3 include the following:

- Part (a) shows that the feedstock must be essentially free, i.e. a waste from another forestry or agricultural industry, to realize a positive NPV without policies to implement incentives (yellow indicates a negative NPV).

- Part (b) indicates that grants to reduce the capital costs that must be paid by the involved companies or a production credit (or premium) on a per kg product basis are both independently effective in allowing for a positive business case. Factors such as expected project life and economies of scale (not discussed here) should be further investigated to determine which type of incentive is best.
- Part (c) shows the importance of optimizing the process to minimize operating costs. With about a 20% decrease in operating costs, the business case becomes positive without the need for incentives or grants. In this study, no heat integration was considered and an average electricity price was used to calculate the cost of part of the energy requirements. Saving on electricity, especially that required for steam generation, and implementing the process in locations where energy is cheaper than the EU average has the potential to make this value chain economically feasible.

The final part of Figure 4, part (d), shows a very high sensitivity of the NPV to the process yield, relative to the other parameters shown in Figure 3. This is indicated both by the steep curves of the chart and the wide range of possible outcomes, from -35 to +53 M€ for the NPV. This result is very important for technology development as it shows that every improvement in the yield of each processing step of the chain can have a dramatic impact on the economics. Also, implementing a production credit or premium magnifies the effect of improvements in yield.

The sensitivity and risk analysis give significant insight into how the economics of this chain may evolve in the future and how policies can affect the outcome. Still, there are several qualitative factors that must be taken into account and cannot be predicted easily with financial parameters, but that also may require incentives and policies to promote the itaconic acid chain. These factors are the focus of continuing studies.

4.7 Environmental impact study

Following the technical and sensitivity analysis, the environmental impact of the value chain was evaluated through a quick-scan life cycle assessment (LCA). The analysis was carried out using the LCA program SimaPro with assistance from TNO Built Environment. The values resulting from the technical analysis-electricity, steam, and fuel requirements-were directly used as inputs into the LCA along with more detailed process data.

4.7.1 System definition

The same steps as used in the other analyses discussed above were also used in the LCA. The system boundaries thus incorporated the biomass collection through the production of the itaconic acid, but did not include the logistics or use of the itaconic acid product (cradle to gate approach). The specific factors that were included and excluded are given below:

Included:

- Production of fuel required for logging equipment
- Production of process steam and electricity
- Production of process chemicals and mediums
- Waste processing

Excluded:
- Transportation equipment and fuel
- Process equipment
- Enzyme production
- Water use

The transportation equipment and fuel were determined to not be significant from previous experience with LCA. The other excluded factors were left out due to insufficient process data that was required as input into the LCA. Previous LCA studies have taken enzyme production into account and have shown the most significant contribution to be in the amount of solids waste.[11] This is not a factor that has been considered in the work presented here, and given the quick-scan nature of the analysis, the omission of this and the other factors was determined to be acceptable. A more detailed full analysis should take these factors into account.

For the electricity and steam production, values were based on averages across Western Europe and included a mix of various energy sources including fossil-based, nuclear, and renewables. The chemicals required for the fermentation medium were taken from a process patent and specified on a per amount itaconic acid produced basis[12], while the chemicals required for the post-processing steps were specified in the data provided by SINTEF.

The production of enzymes for the hydrolysis and yeast for the fermentation steps was not considered here. It is known that the production process requires a significant amount of energy and generates solid waste, but specific values were not available. Furthermore, the amount of enzymes and yeast required per amount product, taking into account recycling or reuse, was unknown. The system boundaries were thus defined to exclude the production process of enzymes and yeast for the LCA while keeping in mind that this may be a significant factor and should be considered in a more detailed study.

4.7.2 Environmental impact method

The CML 2000 method was used in this analysis as it is widely accepted both within and outside of the Netherlands. The CML defines how the process inputs are used to determine the environmental factors. More detailed descriptions of the method and its outputs can be easily found in literature[13], but a list is given here:
- Abiotic mineral resources depletion potential (ADP)
- Global warming potential (GWP)
- Ozone depletion potential (ODP)
- Human toxicity potential (HTP)
- Fresh water aquatic eco-toxicity potential (FAETP)
- Marine aquatic eco-toxicity potential (MAETP)
- Terrestrial eco-toxicity potential (TETP)

[11] G. Zhi Fu, et al., “Life cycle assessment of bio-ethanol derived from cellulose,” *Int. Journal of LCA* **8** (2003).
[12] A. Jarry, et al., “Production of itaconic acid by fermentation,” *United States Patent no. 5,637,485*, (1997).
[13] http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html

- Photochemical ozone creation potential (POCP)
- Eutrophication potential (EP)
- Acidification potential (AP)
- Land competition (LC)

Two energy indicators were also added during the analysis:
- Non-renewable energy use (NREU)
- Renewable energy use (REU)

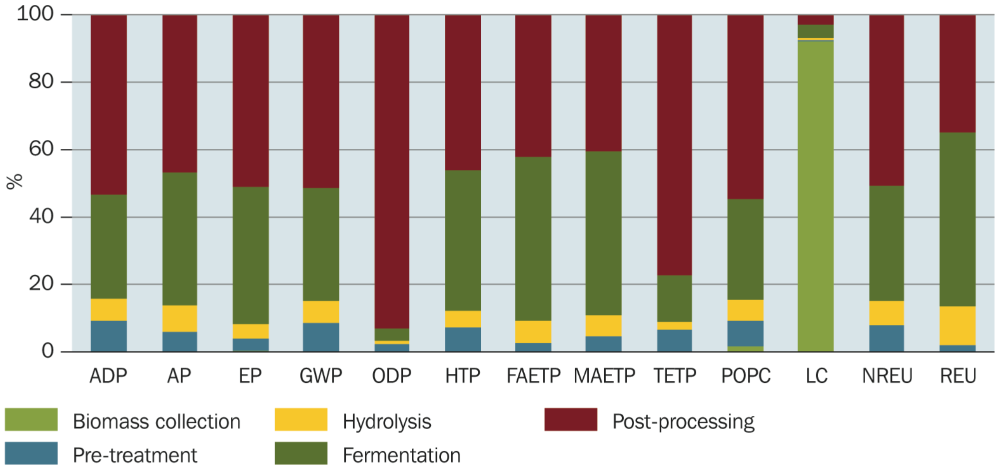


Figure 5 LCA results showing the relative contribution of each of the process steps to the impact factors.

4.7.3 *Results*

The results of the LCA are shown in Figure 5 as the relative contribution of each of the process steps to the various environmental impact factors. The non-renewable energy usage (NREU) and renewable energy usage (REU) are also given. It is immediately clear from the chart that the fermentation and post-processing steps have the largest environmental impacts. This is mostly due to the energy requirements, as also indicated in Figure 1, but also due to the chemicals involved in the process, a factor not considered in the technical analysis. For example, the post-processing requires a substantial amount of hydrochloric acid, the production of which contributes 17% of the total GWP and causes the majority (> 80%) of the ODP factor. Also, the fermentation medium includes copper nitrate and was shown to be a major contribution to the HTP. Further analysis showed that this was due to a significant amount of arsenic associated with the production of the copper metal. Table 5 gives the absolute values for the same set of results along with the units for each of the environmental impact categories.

Table 5 Absolute values for the environmental impact factors per kg itaconic acid produced resulting from the LCA for each of the process steps. The shadow price per kg equivalent is also given for each category.

Impact category	*Unit*	*Total*	*Biomass collection*	*Pre-treatment*	*Hydrolysis*	*Fermen-tation*	*Post-processing*	*Shadow Price (€/kg eq)*
ADP	kg Sb eq	0.0534	5.67E-05	0.00487	0.00349	0.0166	0.0284	0
AP	kg SO_2 eq	0.0279	6.19E-05	0.00161	0.00221	0.0110	0.0131	4
EP	kg PO_4^{3-} eq	0.00252	1.37E-05	8.68E-05	0.000115	0.00102	0.00129	9
GWP	kg CO_2 eq	7.13	0.00839	0.610	0.473	2.40	3.64	0.05
ODP	kg CFC-11 eq	2.72E-06	1.10E-09	6.91E-08	2.07E-08	1.05E-07	2.52E-06	30
HTP	kg 1.4-DB eq	1.92	0.00479	0.137	0.0970	0.796	0.884	0.08
FAETP	kg 1.4-DB eq	0.539	0.000221	0.0143	0.0351	0.262	0.227	0.04
MAETP	kg 1.4-DB eq	1424	0.289	69.1	89.3	689	576	0.0001
TETP	kg 1.4-DB eq	0.0426	5.44E-06	0.00289	0.000964	0.00589	0.0328	1.3
POPC	kg C_2H_4	0.00227	4.13E-05	0.000174	0.000138	0.000680	0.00124	2
LC	m^2 $year^{-1}$	0.345	0.318	0.000567	0.00281	0.0131	0.0103	No value
NREU	MJ	132	0.130	10.6	9.59	45.0	66.5	n/a
REU	MJ	4.44	0.000489	0.0988	0.502	2.29	1.54	n/a

Another interpretation of the LCA results is given by the *shadow price* of each step for the various impact factors. The shadow price is defined as the point where prevention costs meet damage costs, based on factors to convert the units of kg equivalents to Euros, as also shown in Table 4.[14] This calculation essentially assigns a monetary value to the environmental burden of each process based on the type of environmental impact that is caused by the process implementation and operation. The methodology for this calculation is a recent development (see note 14 below), but has since been widely accepted.

The results of the shadow price calculation are shown in Figure 6 for each impact category, with the contribution from each process step also given. The global warming potential (GWP) is by far the most expensive damage to avoid, again because of the high energy production requirements of the fermentation and post-processing steps that emit large amounts of CO_2 and other green house gases. This also adds a significant contribution to the acidification potential (AP) and human toxicity potential (HTP) factors, along with the environmental damage from the production of the various required chemicals. Finally, the land use change (LC) is also shown to be significant, almost completely due to the land needed for the production of the wood feedstock. The pine wood considered in this study is a 2nd generation feedstock, i.e. it does not compete with the food supply, but will still utilize land that could otherwise possibly be used for agriculture.

The total over each of the categories is calculated to be €0.82/kg itaconic acid produced. With the production cost of about €3.23/kg calculated from the technical analysis, the environmental impact adds an additional 25% in costs. Adding the two costs together gives €4.05/kg, which is significantly higher than the market price of itaconic acid, currently at €3.25/kg.

[14] T. van Harmelen, et al., "The price of toxicity: Methodology for the assessment of shadow price for human toxicity, eco-toxicity, and abiotic depletion," *Eco-Efficiency in Industry and Science, vol. 22* (2007).

The costs of the environmental impacts will not be incurred directly by the companies involved in the value chain, but when considering the overall long-term picture and benefits of implementing the process for a local economy, the total cost is important to realize.

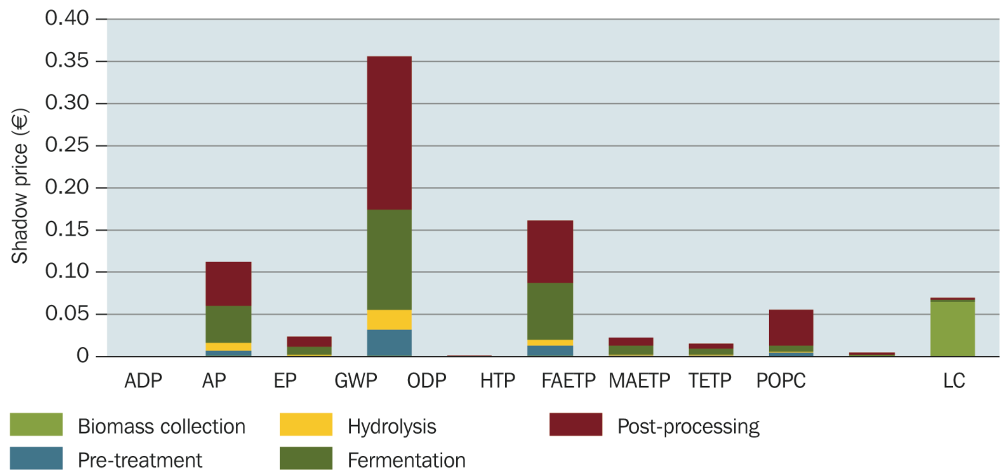


Figure 6 Results for the calculation of the shadow price for each process step and impact category. Total over all categories = €0.82/kg itaconic acid produced.

A final result of the LCA was the benchmarking of the itaconic acid chain against that for acrylic acid based on the same environmental impact factors. The results are shown in Figure 7 as relative values for each category. It is immediately clear that the results are not positive as in every case the acrylic acid is found to have a lesser impact than the itaconic acid. The shadow costs of acrylic acid were calculated to be about 6 times lower than those of itaconic acid (see Figure 8). This was expected to some degree from the results of the technical analysis that showed much lower CO_2 emissions for the production of acrylic acid than for itaconic acid. Again, the acrylic acid process is part of the oil refinery process and has been highly optimized over the years. The emissions and other factors are thus distributed over the several products associated with oil refining. It should be noted, however, that although acrylic acid production requires less energy than the itaconic acid production, the relative fraction from non-renewable energy sources is much higher for acrylic acid. This is expected due to the integration with oil refining and use of fossil fuels for the feedstock and shows that as non-renewable energy sources become more expensive and scarce, the impact will be greater for the production of acrylic acid that for the production of itaconic acid. With a higher contribution of renewable energy sources to the energy mix, the environmental impact of the itaconic acid has much more potential for being lessened.

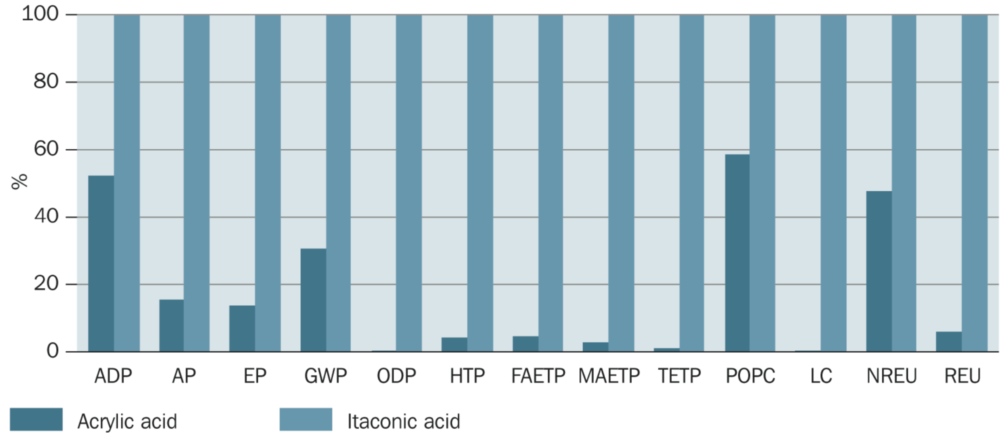


Figure 7 Benchmarking results for the itaconic acid chain against conventional acrylic acid for the impact factors.

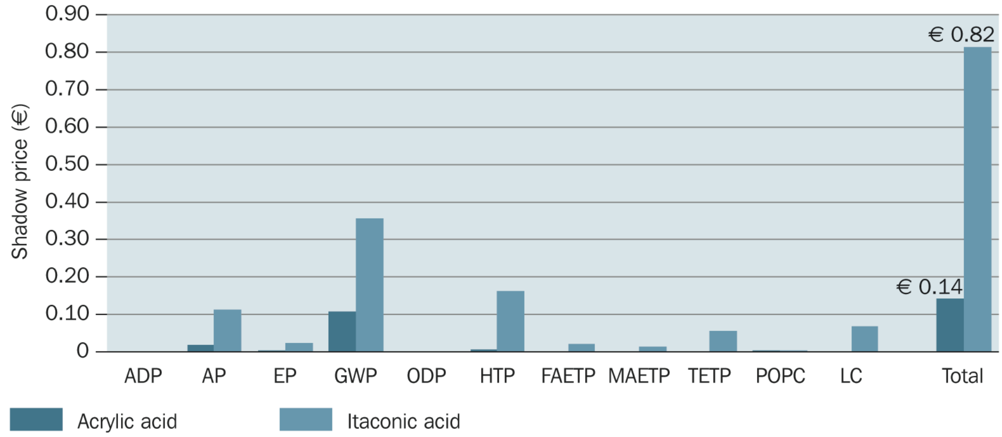


Figure 8 Comparison of the shadow price for 1 kg acrylic acid and 1 kg itaconic acid.

4.8 Conclusions

The process to produce itaconic acid from a pine wood feedstock utilizing a steam explosion pre-treatment was thoroughly analyzed through the technical aspects of each step, the financial parameters, and a quick-scan life cycle assessment. The results were then benchmarked against the production process for acrylic acid, the conventional fossil-based chemical that itaconic acid would most likely replace. The results were not positive for itaconic acid due to the high costs, high energy requirements, associated CO_2 emissions, and other environmental impacts. It should be noted that this is not necessarily the optimal production chain. Different feedstock/pre-treatment/processing combinations may give dramatically different results. Furthermore, recent developments in technologies different than those analyzed have already shown significant improvements, like low-pH fermentations.

An advantage of this value chain was the low sensitivity to the cost of feedstock. As bio-based chains become increasingly prevalent, there is potential for increased feedstock prices due to higher demand.

The high value of the itaconic acid makes this much less of a factor than when biomass feedstocks are used for low value products, such as electricity generation or fuels.

Further analysis showed that economically positive production of itaconic acid could be realized by implementing a 14% premium on the price of itaconic acid, to be added to the purchase price or paid by government funding. Alternatively, other aspects of the process could also be improved to result in a positive business case. These were found to be an increase of about 20% in the process yield or a decrease in 20% for total operating costs. Increase in process yield can be obtained when hemi-cellulose is utilized. In fact, amongst others, ethanol research shows it is possible. The decrease in operating costs could in turn be realized by a 90% decrease in feedstock cost, for example by using essentially free waste wood, or a 48% decrease in energy usage. Part of this can be realized by combustion of lignin. The increase in process yield is especially advantageous as it would further have the effect of reducing the environmental impact with less use of chemicals and energy per unit of itaconic acid produced. This result is one of the key results of this study and suggests that focusing research on the improvement of the process yield or energy efficiency would be the most effective allocation of resources.

5 Production of ethanol from wheat straw

5.1 Management summary

The production of ethanol from bio-based sources is a well-known technology, but utilizing ligno-cellulosic 2nd generation feedstocks is still in development. The analysis was carried out on the chain converting wheat straw, an agricultural waste product, through mild acid pre-treatment, simultaneous saccharification (hydrolysis) and fermentation, distillation, and dehydration to yield fuel grade (99.6%) ethanol. Data was obtained from a report which incorporated experimental results, including the utilization of a newly developed enzyme that gave a 33% increase in the straw-to-ethanol yield. With the extensive global ethanol market, it was determined that feedstock supply would mostly likely be the limiting factor in implementation of the bio-ethanol chain. Therefore, increases in the process yield and the effect on the economics were investigated for this value chain.

The calculations for the technical analysis were based on a production capacity of 150 ton ethanol/yr. No single step or parameter dominated the capital or operating costs, which were calculated to be 79.8 M€ and 82.5 M€/yr, respectively. The energy requirements of 358 GWh/yr, or 8600 GJ/ton ethanol, were much higher than for conventional fossil-based ethanol production, 58 GJ/ton. However, the bio-based process produces a significant amount of waste, mostly lignin, which can be combusted in a combined heat and power plant. This can produce about 344 GWh/yr electricity, so that the net energy demand becomes only 14 GWh/yr, or 336 GJ/ton, and was largely due to the fuel requirement for harvesting the wheat straw. The CO_2 emissions were also calculated and found to be 164 kton/yr. This was only slightly higher than the value for the fossil-based process, but the benefit of the bio-based process was in the source of the emissions; 47% of the emissions were from the fermentation process with a much lower environmental impact than the fossil sources of CO_2.

The economics were very positive for this chain, resulting in an NPV of 102 M€ after 10 years and an IRR of 26%. A sensitivity analysis was carried out and showed the market price, operating costs, feedstock costs, and yield to be the most important factors, in that order. At an increase of 45% or higher in the price of the feedstock, a possible scenario given the likely increase in demand for ligno-cellulosic feedstocks, the NPV becomes negative. The same situation was predicted for a 15% decrease in market price, a 20% increase in OPEX, or a 40% decrease in yield. Given the increasing demand for bio-ethanol, the possibility to lower operating costs by producing the process electricity from waste combustion, and the continuing research to improve the yield, these factors were not thought to introduce significant risk into implementing the value chain.

The general conclusions from the analysis were that the value chain is promising. Using agricultural waste as the feedstock, especially if it can be collected at the same time as the primary agricultural product, and producing the process electricity by combustion of the process waste dramatically improve the process sustainability relative to the conventional fossil-based process. Feedstock supply could be an issue with large scale implementation of the value chain and increased demand, but the other factors — market price, operating costs, and yield — have more impact on the economics and are expected to improve.

5.2 Chain description

This chain is focused on the production of (bio-)ethanol from wheat straw through a fermentation chain. The production of ethanol from biomass feedstocks is a well known process, but has typically utilized feedstocks with easily extractable sugars that compete with food supply ("first generation feedstock"). The wheat straw considered in this chain is a residue of grain harvesting, and thus is a second generation, lignocellulosic feedstock. The chain was analyzed extensively in a 5-year (2002-2006) Dutch research project involving several partners including ECN and TNO. The final project report including experimental results and LCA analysis was used to obtain the data used in this study.

The steps of the chain that have been evaluated are the following:

- *Collection of biomass*. The wheat straw is a residue from grain harvesting, but still must be collected from the fields, baled, stored, and finally transported by truck to the processing plant. A collection area at a distance of 20 km was assumed, but this was shown in the reference report to not have a large impact on the overall chain. The calculations were based on a moisture content of 11% for the straw; any drying of the straw needed before the transportation to the processing plant was not specified.
- *Milling*. The straw must be milled before any chemical treatment processes. This was assumed to be part of the bio-ethanol plant. The energy requirements were measured experimentally as part of the Dutch study.
- *Pre-treatment*. The process considered was a mild acid thermal pre-treatment. As part of the reference study, the process conditions were investigated experimentally to optimize the downstream yields.
- *Hydrolysis and fermentation*. The hydrolysis and fermentation steps were combined into one "simultaneous saccharification and fermentation" step, as per the experimental results giving the best yield the ethanol in the reference study. It was also reported in the study that a new yeast had been developed at the Delft University of Technology that allowed for a yield of 250 L ethanol/ton wheat straw, where only 180 L/ton had been realized before. The new yeast was made available for the experiments that were part of the study, and so is also considered here.
- *Distillation and dehydration*. The output of the fermentation process was distilled and dehydrated to result in fuel grade ethanol at 99.6 wt% with a final yield of 0.22 kg ethanol/kg wheat straw (dry weight basis).

The final product of the chain is only the ethanol. Its use as a fuel or industrial feedstock will not be discussed. Also, the logistical requirements for the storage and transport of the final product were not considered. These are factors that are influenced by the choice of a centralized processing plant (of a large scale) or decentralized processing (with smaller transportation distances for the feedstock). This is beyond the scope of the work presented here, but previous estimates have shown that this is expected to make a difference of only 1% of the final cost of the ethanol. A larger issue, however, are the emissions and sustainability associated with the transportation (usually be diesel-fueled trucks) and should be the focus of further studies.

5.3 Conventional process

The conventional production of ethanol is a petro-chemical process. A full detailed analysis has not been done here, but cumulative values over the entire production chain for fossil-fuel based ethanol were found in the literature.[15] This included the emissions from the extraction of fossil fuels and the emissions associated with the production of the process steam and electricity requirements. The available relevant parameters are:

- Energy demand = 58.0 GJ/ton
- CO_2 emissions = 1990 kg/ton

The costs of the system are not available, but given the long-term establishment and optimization of the petroleum industry, a large percentage of both the capital and operating costs are expected to be shared over several products. The market price of industrial grade ethanol (99.6 wt%) is currently about 0.71 €/L in Europe[16] with some sensitivity to market trends and oil prices and regional variances (± .02 €/L).

5.4 Potential of value chain

5.4.1 Market

Data for the current global market is not readily available, however it can be estimated based on the European and the United States markets. In the United States, the demand for ethanol is greatly increasing and is expected to be 53 billion liters for the fuel additives sector alone by 2012.[17] In Europe, this same sector is expected to be about 4.7 billion liters of ethanol by 2015 and is expected to grow substantially in the coming years due to the ambitious targets set by European directives for the use of bio-fuels in blended motor fuels (8% by 2015 and 10% by 2020).

[15] M. Patel, "Cumulative energy demand (CED) and cumulative CO_2 emissions for products of the organic chemical industry," *Energy,* **28** (2003).
[16] http://www.icis.com/v2/chemicals/9075312/ethanol/pricing.html, accessed 5 November 2010.
[17] P. Gallagher, "Ethanol Industry Situation and Outlook," *Iowa State University Extension Report*, 2006.

This is already evident in the trends specifically for bio-based ethanol demand, with a rapid growth in Europe from 0.41 billion liters in 2001 to 2.5 billion liters in 2008.[18] Furthermore, only 25.6% of the bio-ethanol consumed in Europe is actually produced in Europe[19], so that even with a constant market size, savings from reduced import duties and improved sustainability can be realized with a larger local market share and reduced transportation distances. Therefore, the market size for ethanol is not seen to be the limiting factor in this value chain.

5.4.2 *Feedstock availability*

Several sources of lignocellulosic biomass are possible feedstocks for this chain (with the specified pre-treatment steps), including corn stover, wheat and rice straw, and cotton stalks. In the US alone, the estimated availability of these feedstocks, primarily from agricultural residues, is estimated to be 156 Mton/yr (dry weight basis).[20] Given the process yield calculated in this study of 0.22 kg ethanol/kg dry feedstock, the potential for bio-ethanol production in the US from domestic feedstocks is 43 billion liters-10 billion liters less than the expected US demand. In Europe, the estimated feedstock supply from similar agricultural residue sources is much less at 70 kton/yr.[21,22] With the same yield, the potential for bio-ethanol production in Europe is 19 million liters per year, two orders of magnitude less than the expected demand in the near future. It is possible to increase this value by taking into account a greater variety of feedstock sources, including forerstry residues and energy crops, to give a maximum amount of bio-ethanol that can be produced in Europe of 38 billion liters, as quoted by the second largest ethanol producer in Europe, Teréos.[23] However, the chain described in this study may not be valid for all sources, especially forestry residues, while other sources will compete with the food supply. It is therefore most probable that the feedstock supply is the limiting factor in the potential of the chain discussed here.

5.5 Technical analysis

Several factors were evaluated for comparing the different chains and individual chain steps: capital investments (CAPEX), operating costs (OPEX), energy requirements, and CO_2 emissions (and equivalents). The values were calculated separately for the collection of the biomass and for the bioethanol plant, including the milling and chemical processing steps. The total values were then used as input into the system analysis software RETScreen for the financial analysis. Figure 9 shows the results for each of the different parameters with the relative contribution from the two main parts of the chain.

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[18] "Bio-ethanol market in Europe," http://www.tomorrowisgreener.com/bio-ethanol-market-in-europe/, accessed 5 November 2010.
[19] Above, n. 3.
[20] "Industrial Bioproducts: Today and Tomorrow," *U.S. Department of Energy, Office of Energy, Efficiency, and Renewable Energy,* March 2004.
[21] "Estimating the environmentally compatible bioenergy potential from agriculture," *EEA*, 2007.
[22] "Straw for energy production," http://www.videncenter.dk/gule%20halm%20haefte/Gul_Engelsk/halm-UK02.pdf, accessed 5 November 2010.
[23] http://www.openpr.com/news/36828/Ter-os-European-ethanol-market-share-max-20-on-domestic-feedstock-in-2030.html, accessed 5 November 2010.

The calculations were based on a plant capacity of 150 kton ethanol/yr with the required feedstock input found to be about 688 kton/yr. More detailed descriptions of the calculations are given in the following subsections along with an explanation of the other values used for input into RETScreen. In particular, in the *Energy and CO_2 Emissions* subsection is a discussion on total CO_2 emissions versus the CO_2 emissions from only fossil sources, as shown separately in Figure 9.

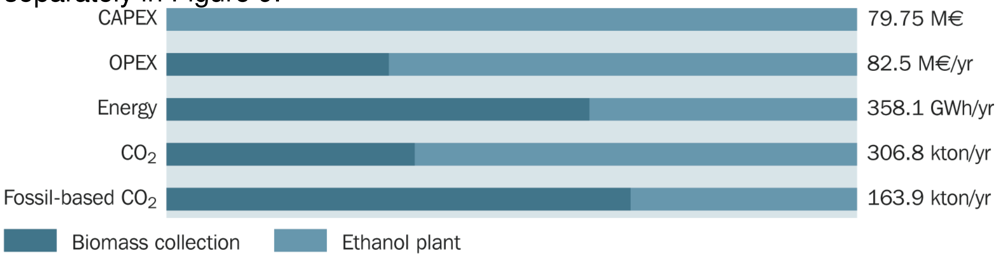

Figure 9 Calculated values of the evaluated factors — CAPEX, OPEX, CO_2 emissions, and energy requirements — over the two parts of the chain, the biomass collection and the bioethanol plant (including the milling and (bio)chemical processing steps). The total values at the end of the chain are also shown.

5.5.1 *Costs*

The break down of capital costs over each step and the operating costs by category (including the feedstock cost) are given in parts (a) and (b), respectively. The cost of the electricity required for the production plant was included in the OPEX calculation using the European average electricity price of .0809 €/kWh. More detailed data was not available or was not provided by the reference report, but it is thought that the most important contributions to the costs are accounted for.

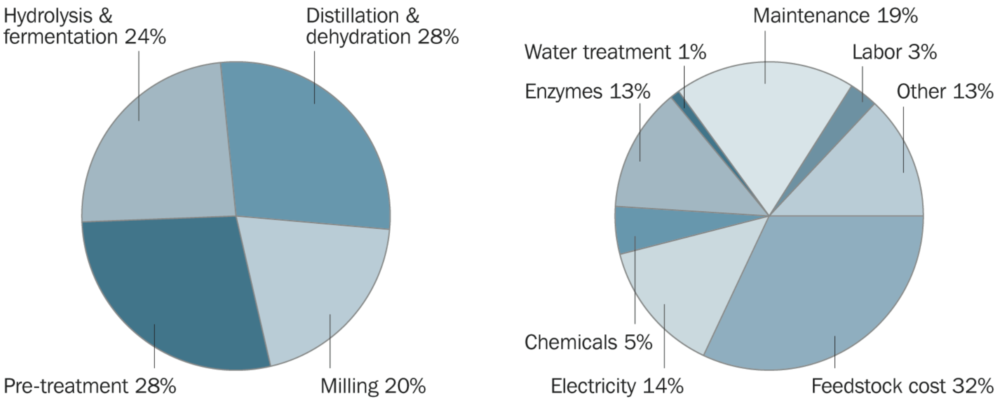

Figure 10 Distribution of the capital costs over the processing steps and operating costs by category.

5.5.2 *Energy requirements and CO_2 emissions*

The energy requirements for the chain included diesel fuel usage, steam generation, and electricity. The consumption of diesel fuel was the only energy requirement for the biomass collection and was calculated based on local data from the Netherlands. The data given for the processes steps combined steam and electricity requirements as one value, already accounting for the differences in efficiency for generating steam versus utilizing primary energy.

The emissions factor associated with the energy requirements for the processing was taken as the average value for OECD Europe for 1999-2002, found to be 387 kg CO_2/MWh electricity.[24] For calculation of the associated CO_2 emissions, the emissions factors were:
- diesel fuel = 3.16 kg CO_2/kg fuel
- electricity generation = 387 kg CO_2/MWh

The other source of CO_2 in this chain is from the fermentation process. This was calculated based on the stoichiometry of the fermentation reaction of C6 sugars to ethanol, yielding one mole of CO_2 for every mole of ethanol.

The total CO_2 emissions for this chain were calculated to be 2050 kg CO_2/ton ethanol produced. This value included the emissions from the farming equipment used to collect the wheat straw feedstock, the emissions directly from the fermentation step (those from the other steps were assumed to be negligible), and the emissions for the energy requirements of the bio-ethanol plant, as described above. It should be noted that no carbon uptake due to the growth of the feedstock or emissions (CO_2 and NO_x) released from the soil during plowing were considered here. The total values from each emission source are given in Table 6.

Table 6 Breakdown of the types of CO_2 emissions over the entire chain.

Type of CO_2 emission	Value (kton/yr)
Non-fossil based emissions (from fermentation)	143
Fossil-based electricity production emissions	53.6
Fossil-based fuel usage emissions	110

5.5.3 *Benchmarking*

Comparing the final value of 2050 kg/ton to that for conventionally produced ethanol, 1990 kg/ton, there at first there seems to be no benefit at all from implementing the bio-based production chain. However, as shown in the Table 6, the emissions should be divided into the three different categories-non-fossil fuel based (from the fermentation step), fossil-based electricity production (from electricity generation), and fossil-based fuel usage (from the farming equipment)-to be accurately analyzed. The non-fossil based CO_2, accounting for 47% of the total emissions, is much cleaner than the fossil-based emissions and is produced at one closed point source (the fermentors). It should be feasible to capture the CO_2 given a tax on carbon or a value-adding use of the CO_2. Not including these emissions in the comparison with the fossil-based benchmark gives a value of 1090 kg CO_2/ton ethanol.

This value is significantly lower than the emissions for the conventional ethanol production chain, but still other factors can be considered. It is possible to make use of the wastes of the process (mostly lignin material) in a combined heat and power (CHP) plant. This produces both heat and electricity for the other processing steps. Furthermore, the effluent can be treated by anaerobic digestion to yield a biogas that can also be combusted.

[24] "Voluntary reporting of greenhouse gases," *U.S. Department of Energy, Energy Information Administration,* October 2007.

From the reference report used to extract the data for this study, the CHP has the potential to produce an excess of 25.0 MW_e (after supplying all the required electricity for the production plant) that can then be sold to the grid. The CHP system almost doubles the capital costs, but saves on operating costs and gives an extra source of income from the sale of the excess electricity. A further benefit is the reduction of the CO_2 emissions as no electricity from fossil sources is used in the process. Considering these factors and the differences between fossil-based and non-fossil-based emission sources, the bio-based ethanol chain is a substantial improvement over the conventional chain.

5.5.4 *RETScreen programming*

The final values from the step-wise analysis of the itaconic acid chain were used as inputs into the system financial analysis, performed in the RETScreen software. The other financial parameters needed in the analysis were based on common values and the European average inflation rate, shown in Table 7.

Table 7 Financial parameters used in RETScreen.

Parameter	Value	Parameter	Value
Fuel cost escalation rate	3.5 %	Debt ratio (% financed by companies)	50 %
Inflation rate	1.8 %	Debt interest rate	5.0 %
Discount rate	10 %	Debt term	10 years
Project life	10 years	Production credit escalation rate	1.8 %

The ability to specify a "production credit" is a feature of RETScreen that allows for a policy incentive or premium to be specified for sustainable products on a €/kg basis. The production credit escalation rate can then be specified to describe how the credit amount changes in subsequent years, either increasing or decreasing. In this analysis, a value of 1.8% was chosen to match the inflation rate and effectively have no change in the credit impact over time.

As it turns out, the production credit was not needed in this case, although with other bio-based chains it has been shown to be essential. The economics of the chain (without considering a CHP plant) were very positive due to the high yield of ethanol from the feedstock. The current market price of ethanol, currently at 0.71 €/L for industrial grade, is high enough to result in a positive business case without any incentives or premiums offered and gives an internal rate of return (IRR) of 26%, with the financial parameters given in Table 7. This is shown in Figure 11 as the cumulative cash flow versus time, which also shows the breakeven point after only two years of plant operation. An IRR of 30% is usually desired for a given process, but this would only require an increase in price to 0.725 €/L, a value well within the range of price fluctuations in Europe.

Another factor that could impact the economics of this chain is the implementation of carbon taxes or credits, currently traded for about €15/Mton. Given that the total emissions of the bio-based chain were actually higher than those for the conventional chain, but that the total for only the fossil-based emissions was significantly lower, this was not considered here.

It is not clear at this time how governing regulations will distinguish between sources of CO_2; however, if policies are put in place which consider the differences (fossil based versus non-fossil based), carbon credits could be a significant source of income.

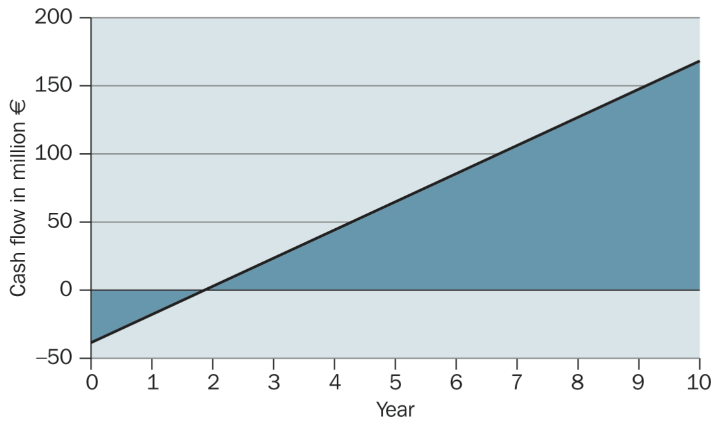

Figure 11 Cumulative cash flow over the first 10 years of the project.

5.6 Sensitivity and risk analysis

A sensitivity and risk analysis was carried out to further investigate the most important factors in the economics of the value chain. The analysis was carried out on the net present value (NPV) of the chain as the best indicator of the financial feasibility. The financial parameters, costs, and production credit were allowed to vary over a wide range of ±100% to allow for effects of policies and incentives not present in conventional industries. Of particular interest for this value chain are the feedstock cost, ethanol market price, and process yield.

Shown in Figure 12 is the impact graph giving the relative contributions of the variability in each key parameter to the outcome of the NPV. The axis at the bottom of the graph does not have any units, but rather presents a relative indication of the strength of the contribution of each parameter. The longer the horizontal bar for a given input parameter, the greater the impact of that parameter on the change in the NPV. The direction of each bar (positive or negative) indicates the relationship between the parameter and the NPV. A positive relationship, for example with the price of ethanol, means that the NPV will increase with an increase in the parameter.

The results show that the most significant parameter in the outcome of the NPV is the price of ethanol, followed by the operating costs (not including the feedstock cost), feedstock costs, capital costs, and production credit rate (or premium), in that order. The effect of the process yield was not analyzed here directly, but is shown in Figure 13. The operating and feedstock costs and the price of ethanol are market driven, so that they are not so easily influenced with the implementation of policies. However, the capital costs can be more easily affected with policies in the form of grants, and its fourth position on the impact chart shows that such incentives may be a good way to promote this value chain.

The production credit rate does not have a significant impact on the NPV, but it could be implemented, for example, with a policy as a set credit amount per amount of ethanol produced sustainably, to make the economics even more favorable relatively directly.

In terms of performing the analysis of a system, the larger bars also indicate which parameters should be studied in the most detail to ensure a high accuracy of the results. For example, an error of 10% in the value for the operating costs will have a much greater impact on the accuracy of the final result for the NPV than an error of 10% in the capital investments.

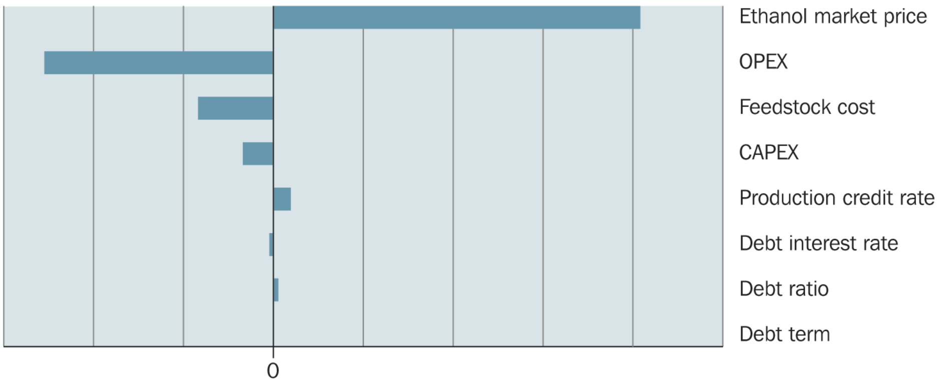

Figure 12 Impact graph showing the relative contribution of the variability in each key parameter to the outcome of the NPV. The axis at the bottom of the graph does not have any units, but rather presents a relative indication of the strength of the contribution of each parameter. The direction of each bar (positive or negative) indicates the relationship between the parameter and the NPV.

To look more closely at the importance of the key parameters in Figure 12, sensitivity analyses were performed on the calculation of the NPV, as shown in the contour plots in Figure 13, where the values indicate the NPV in million €. As the feedstock cost is the most uncertain parameter in how it will change with a more widespread implementation of large scale biomass usage, it was used in each analysis to show how the other indicated parameters would need to change given large fluctuations in the cost of biomass. The starting values for the parameters were those from the results of the step-wise analysis of the full chain:

- Feedstock cost = 38.5 €/ton
- CAPEX = 79.75 M€
- OPEX excluding feedstock cost = 82.5 M€/yr

The process yield was also analyzed by keeping the production of ethanol constant at the 150 kton/yr value. The required feedstock, calculated to be 688 kton/yr or a yield of 218 kg ethanol/ton feedstock, was then varied to simulate changes in the yield of ±50%. This affected both the costs of the feedstock and enzymes required for the hydrolysis while the other costs remained constant. The result, shown in part (d) of Figure 13 showed a moderate sensitivity of the NPV to the process yield.

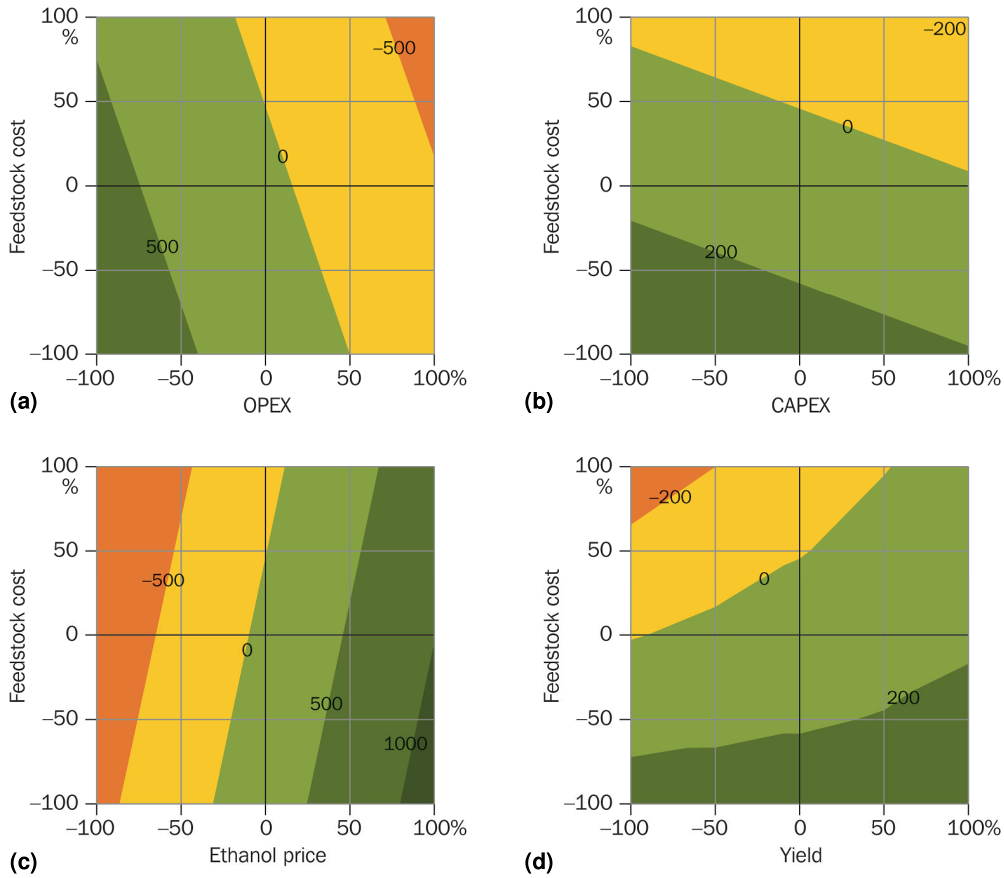

Figure 13 Sensitivity of the NPV to the top key parameters. Values shown are in M€.

The results clearly show the relationships between the NPV and the feedstock cost, CAPEX, OPEX, ethanol price, and yield as expected from the impact chart of Figure 12. Particular features to note that are not seen from Figure 12 include the following:

- Part (a) shows that even with a 100% increase in the cost of biomass feedstock, a positive business case is still possible with further development in the process to reduce the operating costs by about 20%. This may be important in the future if the demand for feedstocks increases significantly.
- Part (b) indicates that if feedstock costs rise significantly, grants to completely eliminate the capital costs burdened by the involved companies will still not result in a positive business case and would essentially be useless. Factors such as expected project life and economies of scale (not discussed here) could be further investigated to determine if other types of grants may have some effect.
- Part (c) shows the high sensitivity of the NPV to the ethanol market price. It is unlikely that the price of ethanol will decrease in the future as it is driven by the costs of production from fossil fuels, for which the costs are not expected to decrease significantly. This is a very positive result as it dramatically decreases the risks associated with rising feedstock costs.
- The final part of Figure 13, part (d), shows a moderate sensitivity of the NPV to the process yield, relative to the other parameters shown in Figure 12, but that the sensitivity increases with increasing feedstock costs.

- This result is very important for technology development as it shows that improvements in the yield of each processing step of the chain can have a significant impact on the economics and allow for a positive business case even with large increases in feedstock costs. As the yield is improved through improvements in biochemical aspects, such as new enzymes for hydrolysis, it is probable that these changes would not require high investments to adapt the existing plants in the future — another very positive result for implementing this chain on a large scale.

The sensitivity and risk analysis give significant insight into how the economics of this chain may evolve in the future and how policies can affect the outcome. Still, there are several qualitative factors that must be taken into account and cannot be predicted easily with financial parameters, but that also may require incentives and policies to promote the bio-based production of ethanol. These factors are the focus of continuing work.

5.7 Conclusions

The chain for the production of ethanol from wheat straw through a fermentation process was thoroughly analyzed through the technical and financial aspects and was shown to be promising. The results were benchmarked against the conventional fossil-based ethanol production process and proved to be more energy intensive, but better in emissions when considering the fossil-based CO_2 versus the much cleaner CO_2 from the fermentation reaction. The economics were also positive with the ethanol market price and operating costs having the most impact.

A sensitivity analysis was carried out and showed the market price, operating costs, feedstock costs, and yield to be the most important factors, in that order. At an increase of 45% or higher in the price of the feedstock, a possible scenario given the likely increase in demand for ligno-cellulosic feedstocks, the NPV becomes negative. The same situation was predicted for a 15% decrease in market price, a 20% increase in OPEX, or a 40% decrease in yield. Given the increasing demand for bio-ethanol, the possibility to produce electricity from combustion of the process waste, and the continuing research to improve the yield, these factors were not thought to introduce significant risk into implementing the value chain.

6 Production of omega-3 fatty acids from micro-algae

6.1 Management summary

Algae are a versatile feedstock that can be cultivated to produce a variety of products, from bio-fuels to high value chemicals. The chain for the production and extraction of omega-3 fatty acid-rich oil from algae was evaluated given the favorable market for omega-3 products. Substantial research showing various health benefits from consuming omega-3's has caused the market to grow rapidly in recent years with the trend expected to continue. The value of omega-3 fatty acids is also high with a market price two orders of magnitude higher than that for bio-diesel.

The analyzed chain included the cultivation of algae in a closed, naturally illuminated tubular bio-reactor assumed to be located in Eindhoven, the Netherlands. The algae were to be harvested and dried by centrifugation with the omega-3-rich oil obtained through supercritical CO_2 extraction. The major contributions to the costs were found to be the circulation pump and labor for the cultivation step. The circulation pump was also the major contribution to the energy requirements along with CO_2 compression for the extraction step. For a 1 ha system yielding 18.5 tons oil/year, the final values over the whole chain were: CAPEX = 1.38 M€, OPEX = 308 k€/yr, and energy requirements = 264 MWh/yr. The total CO_2 emissions were low at 26 ton/year, in part due to the consumption of 1.86 g CO_2/g dry weight of algae grown.

The economics were positive for this chain, showing an NPV of 1.7 M€ after 10 years and an IRR of 25%. The market price of the extracted product had the most impact on the results, emphasizing the importance of choosing the right product to promote in the algae cultivation. The results were also moderately sensitive to the CAPEX, OPEX, and yield, with the yield sensitivity increasing with increasing product market price. A minimum market price of €26/kg was found with no changes in any of the parameters.

The general conclusions from the analysis were that algae are an interesting feedstock to produce high value products, but not to produce low value commodities such as fuels. The chain is economically attractive and more sustainable than the largest current source of omega-3's, fish oil, but is not yet well established and is potentially risky given the sensitivity of the algae to contamination and environmental conditions. The yield of oil from the algae will be difficult to increase significantly, so research should be focused on lowering costs by allowing for higher culture densities and decreased pumping requirements for circulation though improved reactor design.

6.2 Chain description

This chain is focused on the production of omega-3 fatty acids from micro-algae though a supercritical CO_2 extraction process. The algae are assumed to be cultivated and harvested from a closed tubular photo-bioreactor (PBR), as it is currently the more commercially viable reactor configuration. Algae are able to produce a wide range of products, including lipids, vitamins, and proteins.

They do not compete with other crops or feedstocks for arable land and can be cultivated at exponential growth rates. For the analysis presented here, omega-3 fatty acids were chosen as the main product due to their high value, growing market, and proven feasibility through existing demonstration plants.

The steps of the chain that have been evaluated in this study are the following:
- *Cultivation*. The algae are grown in a closed PBR in a continuous process. CO_2 and other nutrients are constantly fed to the algae while the medium is pumped though tubes and artificially illuminated.
- *Dewatering*. Concentration of the algae slurry is accomplished with centrifugation. Harvesting of the algae is also included with this step as it not a large contribution to the energy requirements and costs of the chain when PBRs are used (for open ponds, harvesting is more difficult and energy intensive).
- *Product extraction*. Several extraction techniques are available for obtaining the products from the algae, including pressing and hexane-based processes. Supercritical fluid extraction (SFE) with CO_2 was chosen as it results in almost 100% yield of products and does not require large amounts of fossil-based organic solvents.

The cultivation of algae has been studied extensively for several applications, especially waste-water treatment and bio-oil production. Either open ponds or closed PBRs may be used. Open ponds have the advantage of utilizing natural sunlight, eliminating the energy requirements for artificial illumination. However, the large surface area makes harvesting difficult and contamination of the culture a significant issue. Closed PBRs are currently much more feasible on a large commercial scale. They can be built in any environment and are much more precisely defined in terms of temperature and illumination intensity.

Processes combining the dewatering and product extraction steps are now in development[25], but not commercially proven yet. The centrifugation of the culture to obtain the algae followed by a separate extraction step is currently the most feasible. SFE with CO_2 for algae is also still in development, but has been proven for other oil extraction systems (e.g. oil from sunflower seeds and rice bran). It offers the advantage of higher purity products, which is especially an important factor when producing high value nutraceuticals and pharmaceuticals that are consumed by people.

6.3 Conventional process

The main source of omega-3 fatty acids is currently fish. The energy requirements and emissions associated with fishing are mostly due to the fuel consumption of the vessels and on-board equipment. A full life cycle analysis was performed based on the fishing industry in Iceland and gave a result of 0.65 L oil and 1.8 kg CO_2 emissions per kg caught fish, on average.[26] Heavy fuel oil is commonly used for fuel onboard marine vessels, with a heating value of about 43 MJ/L, and results in an energy requirement of 28 MJ/kg fish.

[25] http://www.originoil.com/products/low-cost-oil-extraction.html, accessed 29 November 2010.
[26] H.R. Eyjólfsdóttir, et al., “Environmental effects of fish on the consumers dish,” http://matis.is/media/, 2003.

The oil yield from fish is 7% by weight, according to one of the largest fish oil producers, Copeinca[27], with an omega-3 content of 0.30 g/gram fish oil.[28] Given that the omega-3 fatty acids are most commonly sold in the 30% concentration, the key values are based on the total amount of oil product and are the following:

- Energy requirements: 0.402 MJ/g omega-3-rich product
- Emissions: 25.7 g CO_2/g omega-3-rich product

Other factors are also important when considering fish as the source of omega-3 fatty acids which are difficult to describe quantitatively. For one, some species of fish are known to contain significant amounts of heavy metals and it is thought that consuming fish oil, especially of lower quality, may lead to heavy metal build-up in people, causing adverse health effects. Another factor is the diminishing supply of wild fish as seas are being over-fished to try and meet the increasing consumer demand. This will only become amplified with a higher demand for omega-3 fatty acids and has implications for the economics (increasing prices for fish and fish-based products) and the environment (possible extinction of some species).

6.4 Potential of value chain

6.4.1 Market

The global market for omega-3 fatty acids is already large at 71.4 Mton (13.6 Mton for Europe alone) worth about €882 million. The growth rate has averaged 10-13% annually in the past few years and is expected to continue to grow rapidly, with only some levelling off.[29]

The main driver for the trends is the increased use of vitamins and supplements that contain omega-3 fatty acids. This follows from several studies showing substantial health benefits from a diet containing the right amount of omega-3's. In particular, heart, joint, and brain health; cognitive functioning and developments, especially for infants and children; management of autism; and decreasing the risk of prostate cancer have all been shown to be improved by the consumption of omega-3 fatty acids. With health-consciousness and medical bills increasing, more and more people are using supplements and choosing for fortified versions of foods and beverages to try to stay healthy and avoid costly visits to the doctor. As most foods and ingredients do not naturally contain omega-3 fatty acids on any significant level, the omega-3's must be extracted from another source, i.e. fish or algae, and added to foods, increasing the value and creating the market.

[27] http://www.allaboutfeed.net/news/fewer-fish-for-copeinca-asa-id4706.html, accessed 29 November 2010.
[28] P.M. Kris-Etherton, et al, *Circulation* **106** (2002).
[29] http://www.icis.com/Articles/2009/11/09/9260250/omega-3-fatty-acid-use-is-growing-rapidly.html, accessed 29 November 2010.

6.4.2 *Feedstock availability*

Utilizing algae as the feedstock is significantly different than relying on crop-based feedstocks, such as wood or corn stover. With algae, there is no limit from land area availability or competition for food. Algae PBR's can be built up in stacks of horizontal tubes in a relatively compact system. Also, with closed systems, the climate and illumination can be carefully controlled when necessary. The current installed capacity is only about 5000 ton dry algal biomass per year[30], but as the technology becomes more mature, it is expected that this will increase significantly.

Another important difference is the growth rate of algae. While crop-based feedstocks grow slowly over the growing season and are harvested only periodically, algae grow and multiply continuously to give exponential growth rates that are constant throughout the year (at least with climate-controlled systems). With the limited number of algae systems now in operation, the feedstock supply is limiting, but this can be overcome with investment and construction of new systems. Naturally-illuminated outdoor closed systems in sunny climates are certainly favorable, but as the economics improve for the value chain, indoor artificially-illuminated systems in less optimal climates will also be economically attractive.

As a final consideration, given the huge potential market for algae-derived high value products-not only nutraceuticals such as omega-3 fatty acids, but also pharmaceuticals, vitamins, and proteins-and an expected lowering of production costs to make algae-based bio-diesel economically feasible, it is probable that eventually feedstock will be the limiting factor. This may end up being due to the lack of new algae reactor systems, but also perhaps due to a shortage of the nutrients that the algae need to grow. These include CO_2, potassium, and phosphorous among others.[31] It is beyond the scope of this report to analyze each of these system feeds, but it should be noted that their demand could increase significantly, perhaps beyond the available supply.

6.5 Technical analysis

Several factors were evaluated for comparing the different chains and individual chain steps: capital investments (CAPEX), operating costs (OPEX), CO_2 emissions (and equivalents), and energy requirements. The values from each successive step of the chain were cumulated with the final values then used as input into the system analysis software RETScreen for the financial analysis. Figure 9 shows the results for the calculation of the key parameters with the relative contribution from each step in the chain. The calculations were based on a feedstock reactor area of 1 ha, yielding a feedstock supply of 41 ton dry weight algae/yr. The resulting production of omega-3-rich oil was found to be 18.5 ton/yr based on an algae oil content of 45% by weight (dry weight basis) and assuming 100% yield from the extraction process.

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[30] R.H. Wijffels and M.J. Barbosa, "An outlook on micro-algal biofuels," *Science* **329** (2010).

[31] http://business.timesonline.co.uk/tol/business/industry_sectors/natural_resources/article4193017.ece, accessed 1 December 2010.

The concentration of omega-3 fatty acids in the algae oil is typically about 30%.[32] Given that this is also the concentration most commonly found for omega-3 products and ingredients, the calculations were based on the total amount of omega-3-rich oil product. More detailed descriptions of the calculations are given in the following subsections along with an explanation of the other values used for input into RETScreen.

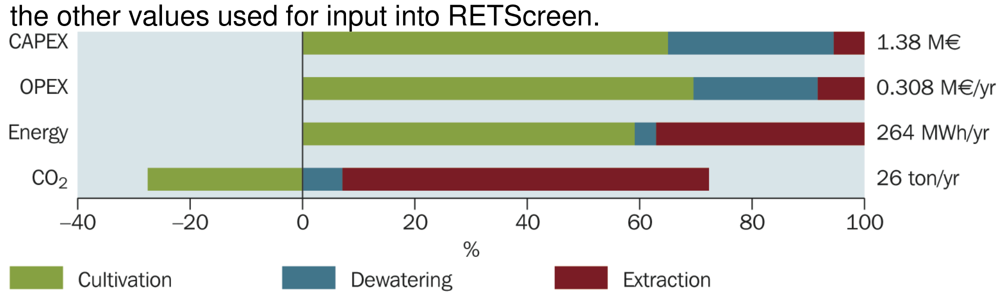

Figure 14 Relative cumulative values of the evaluated factors — CAPEX, OPEX, and energy requirements — over each step of the chain. The final values at the end of the chain are also shown.

6.5.1 *Costs*

The break down of both CAPEX and OPEX (including the feedstock cost) are given in Table 8 with a short description of what was considered for each value. The costs for the cultivation and dewatering steps were obtained from a recent article based on Dutch conditions[33] while the data for the extraction was obtained from a process analysis of SFE with CO_2 for sunflower oil extraction[34] and adjusted for the differences in yields. The data from both references was very detailed and included costs of equipment, labor, energy, maintenance, installation, and other factors. For the cultivation step, the cost of CO_2 was also included as given with the rest of the data. However, the source of CO_2 can be very dirty with no purification required before being fed to the algae, even possibly still absorbed in a CO_2 capture solvent. This is an area of ongoing research and the CO_2 to be fed to the algae may eventually become essentially free. The effect of the price of the CO_2 is investigated through a sensitivity analysis, discussed in a later section.

Table 8 Data obtained for the CAPEX and OPEX of each step.

Process step	**CAPEX (k€)**	**OPEX (k€/yr)**	**Description**
Cultivation	902	215	Medium preparation, culture circulation, blower, CO_2 feed
Dewatering	406	68.2	Harvesting tank, centrifugation
Extraction	72.8	25.3	CO_2 compression and cost; column reactors

[32] E. Morita, et al., “Docosahexaenoic Acid Production and Lipid-Body Formation in Schizochytrium limacinum SR21,” *Marine Biotechnology* **8** (2006).
[33] N.-H. Norsker, et al., “Microalgal production – A close look at the economics,” *Biotechnology Advances* (2010).
[34] M. Bravi, et al., “Process optimization in sunflower oil extraction by supercritical CO_2,” *Chem. Eng. Sci.* (2002).

6.5.2 *Energy requirements and CO_2 emissions*

The energy requirements for the chain included only the electricity needed to run the equipment. Closed tubular reactors were assumed as well as natural illumination. The illumination intensity was based on the monthly average irradiation for Eindhoven, the Netherlands, reaching a peak of about 5000 Wh/m^2/day in June and having an annual average of about 3000 Wh/m^2/day.[35] The data for the cultivation and dewatering steps were given in terms of costs and were converted into energy units using the Dutch national average industrial electricity price of 0.141 €/kWh.[36] The largest contribution by far was the power required for the circulation pump for the algae cultivation, followed by the power for the compression of the supercritical CO_2, as shown in Figure 15. The total energy requirement was 264 MWh/yr, or 0.052 MJ/g omega-3 product.

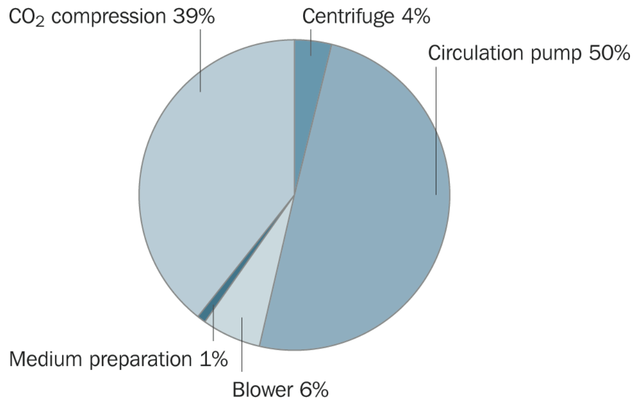

Figure 15 Distribution of energy requirements over the full chain.

The value for the CO_2 emissions for electricity production used in the calculations was the average value for OECD Europe for 1999-2002, found to be 387 kg CO_2/MWh electricity.[37] The total CO_2 emissions for this chain were calculated to be 26.0 ton CO_2/yr, or 1.41 g CO_2/g omega-3 product. This value included the uptake of CO_2 by the algae growth, 1.86 g CO_2/g algae by dry weight, and the emissions from the electricity production.

6.6 Benchmarking

Comparing the final values of 0.052 MJ/g and 1.41 g CO_2/g for algae-based production of omega-3's to those for fish-based production, 0.402 MJ/g and 25.7 g CO_2/g, there is an obvious environmental benefit with the algae-based chain over the conventional fish-based process. However, other factors must be taken into account. First, the production of fish oil is part of a larger process. The values were corrected for the yield of fish oil from a kg of fish caught, but the fish oil may be considered as a by-product of the process to catch fish for food and fish meal. In that case, the energy and emissions could be considered to be zero (the same energy would be used and CO_2 emitted whether or not the fish oil was produced). The other significant factor is the establishment of the industry.

[35] Above, no. 9.
[36] http://www.energy.eu/#industrial, accessed 24 November 2010.
[37] "Voluntary reporting of greenhouse gases," *U.S. Department of Energy, Energy Information Administration,* October 2007.

The fishing industry is well established globally with large investments already made in ships and equipment. The algae industry, on the other hand, is relatively new with far fewer companies involved and several processing aspects still in the research and development phase. It is much riskier to rely on algae as the main producer of omega-3 fatty acids to supply the increasing demand. Also, the impact of a decrease in demand for fish oil due to increased algae production on the total energy and emissions from the fishing industry is difficult to predict.

RETScreen programming
The final values from the step-wise analysis of the algae-based omega-3 fatty acid chain were used as inputs into the system financial analysis, performed in the RETScreen software. The other financial parameters needed in the analysis were based on common values and the European average inflation rate, shown in Table 9.

Table 9 Financial parameters used in RETScreen.

Parameter	Value	Parameter	Value
CO_2 cost escalation rate	1.8 %	Debt ratio (% financed by companies)	50 %
Inflation rate	1.8 %	Debt interest rate	5.0 %
Discount rate	10 %	Debt term	10 years
Project life	10 years	Production credit escalation rate	1.8 %

The ability to specify a "production credit" is a feature of RETScreen that allows for a policy incentive or premium to be specified for sustainable products on a €/kg basis. The production credit escalation rate can then be specified to describe how the credit amount changes in subsequent years, either increasing or decreasing. In this analysis, a value of 1.8% was chosen to match the inflation rate and effectively have no change in the credit impact over time.

As it turns out, the production credit was not needed in this case, although with other bio-based chains it has been shown to be essential. The economics of the chain were very positive due to the high value of the omega-3 product, currently at a market price estimated at €40/kg.[38] With the financial parameters given in Table 9, the internal rate of return based on the assets was very positive at 24.7%. The results are shown in Figure 16 as the cumulative cash flow versus time. At the end of 10 years, the profit is calculated to be €3.29 million with a profit of about €350-450 thousand each year, about 0.05% of the current market. The equity payback occurs after only 1.9 years.

[38] M. Harel, et al., "Advanced DHA, EPA and ArA enrichment materials for marine aquaculture using single cell heterotrophs," *Aquaculture* **213** (2002).

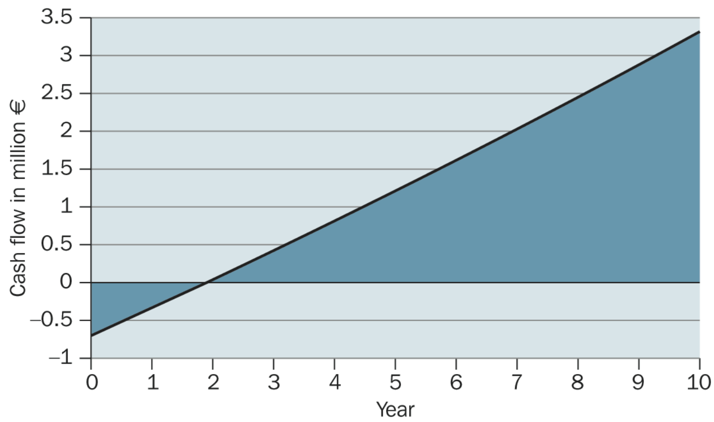

Figure 16 Cumulative cash flow over the first 10 years of the project.

6.7 Sensitivity and risk analysis

A sensitivity and risk analysis was carried out to further investigate the most important factors in the economics of the value chain. The analysis was carried out on the net present value (NPV) of the chain as the best indicator of the financial feasibility of the chain. The financial parameters and costs were allowed to vary over a wide range of ±100% to allow for effects of policies and market changes not present in conventional industries. Of particular interest for this value chain were the cost of CO_2, the market price of the product, and the OPEX.

Shown in Figure 17 is the impact graph giving the relative contributions of the variability in each key parameter to the outcome of the NPV. The axis at the bottom of the graph does not have any units, but rather presents a relative indication of the strength of the contribution of each parameter. The longer the horizontal bar for a given input parameter, the greater the impact of that parameter on the change in the NPV. The direction of each bar (positive or negative) indicates the relationship between the parameter and the NPV. A positive relationship, for example with the price of omega-3 fatty acids, means that the NPV will increase with an increase in the parameter.

The results show that the most significant parameter in the outcome of the NPV is the price of omega-3 products, followed by the operating costs (not including the CO_2 cost), CO_2 cost, and capital costs, in that order. The effect of the process yield was not analyzed here directly, but is shown in Figure 18. The high value of the product completely dominates the business case for this chain.

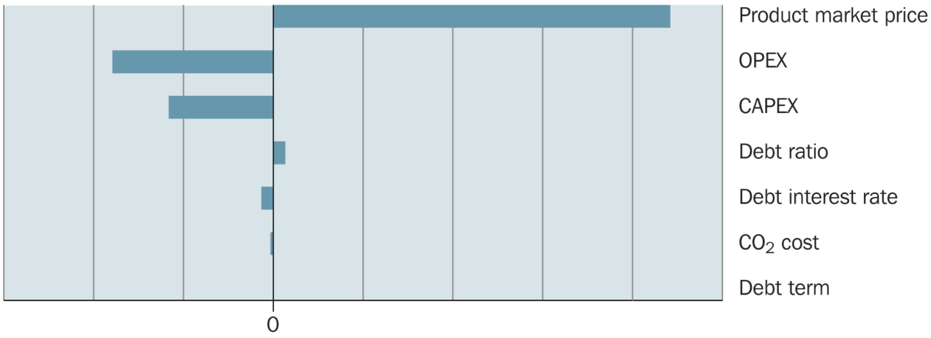

Figure 17 Impact graph showing the relative contribution of the variability in each key parameter to the outcome of the NPV. The axis at the bottom of the graph does not have any units, but rather presents a relative indication of the strength of the contribution of each parameter. The direction of each bar (positive or negative) indicates the relationship between the parameter and the NPV.

For comparison, the same analysis was carried out assuming the algae were grown to produce bio-diesel oil with a much lower value of only €0.40/kg.[39] The business case becomes very negative with a net loss of €4.8 million after 10 years. The costs become much more important, as shown in the impact graph in Figure 17. The dramatic differences in the results show the benefit of producing high value chemicals from algae, as long as the market demand allows, even though much of the emphasis in research and development of these systems is placed on the production of low value algae-based fuels.

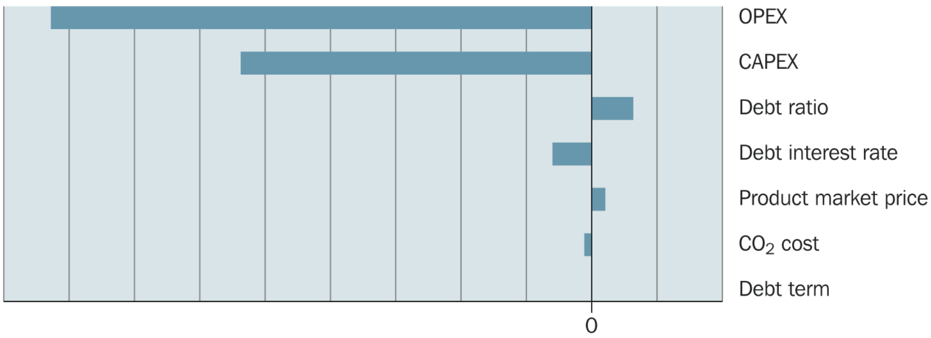

Figure 18 Impact graph for case with production of low value bio-diesel with a market price of €0.40/kg.

To look more closely at the importance of the key parameters for this value chain, sensitivity analyses were performed on the calculation of the NPV, as shown in the contour plots in Figure 19, where the values indicate the NPV in million €. The trends are as expected from Figure 15 and Figure 17: a moderate sensitivity to operating costs with high value products, but a much higher sensitivity with lower value products. The cost of CO_2, the next factor down in the impact chart, was not a large factor while the yield of product from the algae had a similar effect on the economics as the product market price.

[39] Above, no 6.

A few key insights can be derived from Figure 18. The first is that the dominance of the market price on the outcome of the economics introduces substantial risk into the business case for this value chain. If omega-3 fatty acids were found to not have the health benefits that the market is built on, for example, or if many more companies became involved such that supply far surpassed demand, the market price would drop and there would be little that could be done to keep the economics positive. Part (a) shows a very low sensitivity to the cost of CO_2 relative to the product of the market price, but also indicates a product value of about €26/kg as the minimum for a positive business case.

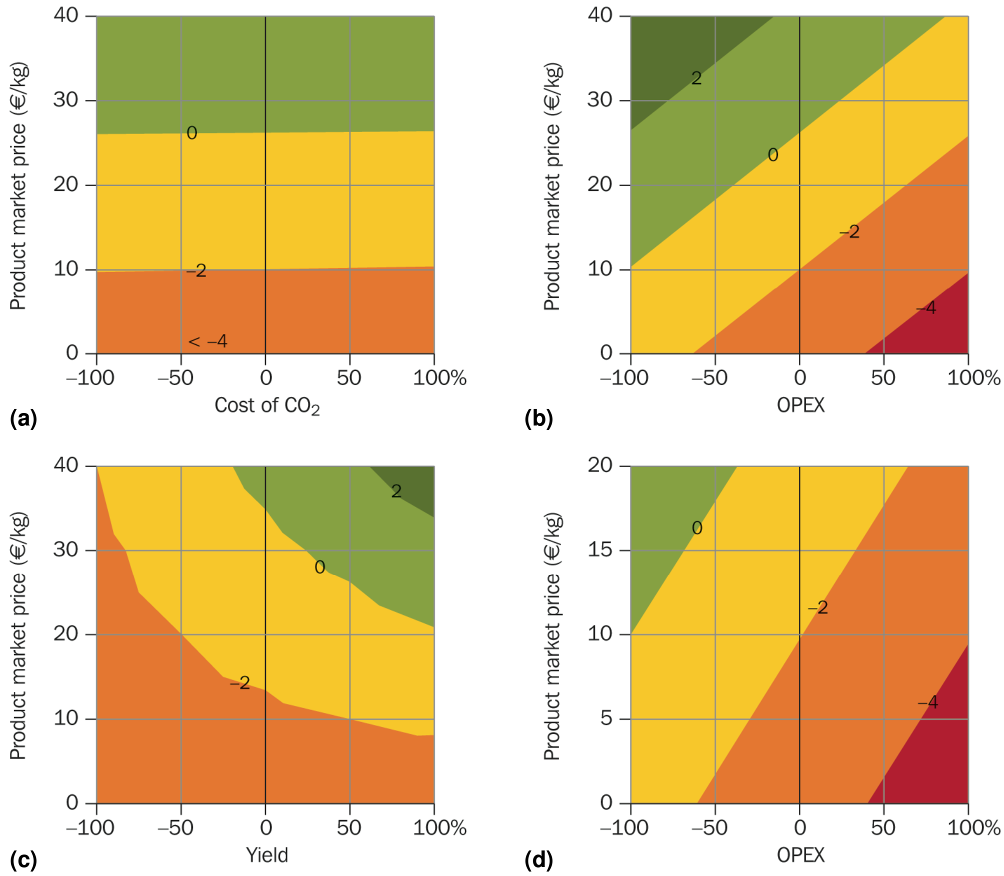

Figure 19 Sensitivity of the NPV to the top key parameters: **(a)** CO_2 cost, **(b)** operating costs, **(c)** and yield. Shown in **(d)** is the sensitivity to the operating costs (with the cost of CO_2 included), but when the algae are made to produce a low value product, such as bio-diesel. Given values are in million €.

The yield is also shown to be significant. With the chain described here, 100% extraction of valuable products is assumed with a production of 45% omega-3-rich oil by weight compared to the dry weight of the algae. It is foreseeable that this will not be able to be increased substantially; a maximum increase of 25% as shown in part (c) is very ambitious. On the other hand, the extraction process described here has not been demonstrated on a commercial scale; a decrease in yield of 50 or even 75% from the ideal may be seen in practice, especially with the earliest implementations.

Finally, the factor that algae are living organisms introduces more risk into the system as changes in environmental conditions (contamination of the culture, temperature drops or spikes, etc.) may kill all or some of a batch so that they no longer produce the desired product. The average yield for a given period of time may drop dramatically, to 75% or lower, and the business case could easily become negative.

Part (d) shows the case for when the algae are designed to produce a low value product, such as bio-diesel. Given the current value of bio-diesel of about €0.40/kg, it is impossible to have a positive business case, even with no operating costs (with the cost of CO_2 included in part (d)). A value of €10/kg, much higher than bio-fuels will sell for, is the absolute minimum for the product value and should be noted when developing algae systems.

6.8 Conclusions

Algae are a promising feedstock for bio-based value chains. They do not suffer from the same limitations as other crop-based feedstocks and can be grown rapidly on a large scale. The specific chain from algae cultivation to extraction of omega-3 fatty acid-rich oil was thoroughly analyzed though both the technical and financial aspects of the process. The results were then benchmarked against the production of omega-3 fatty acids in fish oil, including catching and processing the fish. The two values used for comparison between the two chains-energy requirements and CO_2 emissions-showed clear benefits for producing omega-3's from algae instead of fish. Other sustainability factors, such as depletion of fish species, were briefly discussed, but could be the focus of more detailed future studies.

The economics for the algae-based production of omega-3 fatty acids were found to be positive with an internal rate of return of 25%. However, the choice of chemical that the algae are designed to produce is a key factor. The market prices for algae-based chemicals vary over a couple orders of magnitude, from €0.40/kg for bio-diesel to €40/kg for omega-3 products. This introduces a significant amount of risk into the business case for the value chain as it is therefore very susceptible to market conditions and fluctuations.

A sensitivity analysis was done to further understand the risks involved and the effects of changes in the key parameters. The most important parameter is the market price of the product — with no changes in the other factors, the minimum price is about €26/kg to realize a positive business case, and even with a reduction in operating costs to essentially zero, the price still must be above €10/kg to cover the capital investment. A decrease in the required capital payments would have the same effect to lower the minimum product price, but it is not foreseeable that a minimum of €0.40/kg could be realized. Alternatively, improvements in the yield of the process can make lower value products more feasible. However, there is a limit to the mass fraction of products in the algae and 100% efficiency was already assumed for the extraction process. This leads to the key result that for algae systems to be economically positive, the process must be designed to produce high value products. The costs can be lowered, but the changes to make low value products, such as bio-fuels, would be drastic — on the order of two orders of magnitude decrease.

Efforts should be focused on factors such as increasing the algae density in the culture (decrease in capital costs per kg algae and operating costs for pumping), improving the reactor design to decrease energy requirements for culture pumping and increase photo efficiency (improved algae growth rates), and modifying the algae to produce still higher value products.

7 Signature

Delft, 13 January 2011
SGI-JBL/VBA

TNO Innovation for life

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