EUROPEAN ROADMAP FOR PROCESS INTENSIFICATION

Creative Energy
Energy Transition

Information

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Front cover illustration

Intensified methane steam reformer based on Micro channel Reactor technology (conventional plant in the background)
Courtesy: Velocys Inc., Plain City, Ohio, USA

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Ministry of Economic Affairs

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CONTENT

PI EXAMPLE **PETCHEM SECTOR** – HIGH-GRAVITY ROTATING PACKED BEDS

Traditional technology

A system of absorption-stripping columns: the main product (HClO) has to be removed as quickly as possible from the reaction environment to prevent its decomposition (1)

PI technology

Reactive stripping in High Gravity (HiGee) Rotating Packed Beds: the reactants are subjected to intensive contact and the product is immediately removed via stripping using high rotating apparatus (2) with a specially designed packing (3)

Benefits

- Equipment size decreased by a factor of ca. 40
- Ca. 15% higher product yield
- 50% reduction of the stripping gas
- 1/3 reduction in waste water & chlorinated by
- Same processing capacity

Photo coourtesy of Dow Chemical Company

PI EXAMPLE **FINEPHARM SECTOR** – MICRO REACTOR

Traditional technology

Stirred Tank Reactor: the reactants are mixed in a large vessel, and the heat is removed through the jacket or a heat transfer coil (1)

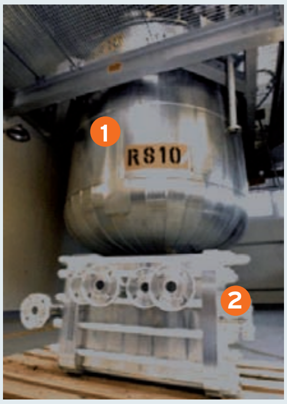
PI technology

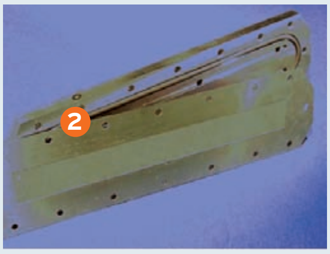
Micro Reactor: the reactants are mixed, and the heat is removed through thousands of micro channels, fabricated by micromachining (2) or lithography

Benefits

- Equipment content 3 liters versus 10 m³
- 20% higher selectivity
  20% higher material yield
- Process more reliable because continuous instead of batch
- Same capacity (1700 kg/h)

Photo coourtesy of DSM an Borshungszentrum Karlsruhe





PI EXAMPLE INFOOD SECTOR – PULSE COMBUSTION DRYING

Traditional technology

Continuous burner-based drying: direct-heated dryers where the drying gas consisting of fresh air, recycled air and the hot combustion gases from a burner is in direct contact with the material to be dry. Direct firing is most commonly applied in textile industry, paper manufacture, chemicals, and agro-food production.

PI technology

Pulse combustion drying: periodic combustion of fuel generates intensive pressure, velocity, and to certain extent, temperature waves propagated from the combustion chamber to the drying chamber. Because of oscillatory nature of the momentum transfer, pulse combustion intensifies the rates of heat and mass transfer thus accelerates drying rates. Technology can be easily retrofitted in the existing dryers!

Benefits

- improved powder quality
- reduced energy consumption by 17-36%
- increased dryer throughput.

(Data on technology applied in 2003 at Berghausen Corporation, Cincinnati, Ohio, USA)

Liquid spray exiting a rotary-valve pulse combustor into spray dryer (Courtesy of Pulse Combustion Systems, San Rafael, CA, USA)

PI EXAMPLE CONFOOD SECTOR – INTELLIGENT CLEANING

Traditional technology

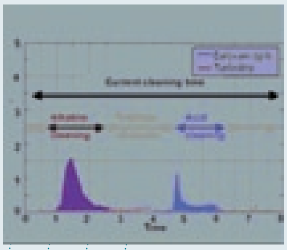
Standardized long cleaning cycles: downtime of food production equipment due to fouling and cleaning; cleaning procedure based on worst case in the past

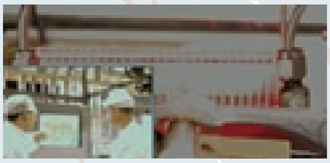
PI technology

Intelligent cleaning: in line sensors measure production and cleaning efficiency; self learning computer models determine optimal cleaning conditions depending on product composition and degree of fouling

Benefits

- Increased capacity; downtime of food processing equipment reduced by 50%
- Decreased use of water and cleaning agents
- Increased flexibility; cleaning conditions automatically adjusted to (new) food composition





EXECUTIVE SUMMARY

Process Intensification (PI) presents a set of often radically innovative principles ("paradigm shift") in process and equipment design, which can bring significant benefits in terms of process and chain efficiency, capital and operating expenses, quality, wastes, process safety, and more.

This Roadmap identifies the potential benefits of PI and expounds on actions that are recommended for the acceleration of PI implementation in the process industry.

The PI Roadmap has been developed for the following sectors:

PETCHEM – Petrochemicals, bulk chemicals
FINEPHARM – Specialty chemicals, pharmaceuticals
INFOOD – Food ingredients
CONFOOD – Consumer food

Process Intensification can address important needs of the process industry, even though these needs vary considerably between sectors; see Figure 1

Importance to sector	PETCHEM	FINEPHARM	INFOOD	CONFOOD

High	– Energy savings
	– Cost competitiveness
	– Safety
	– Regulation
		– Selectivity
		– Cost competitiveness
		– Sustainability
		– Lead time
			– Cost competitiveness [2]	– Cost competitiveness
				  – Yield
				  – Line availability
				– Product quality
				– Food safety
				– Product functionality

Medium	– Social impact – Reliability [1]	– Safety [1] – Reliability [1]	– Selectivity on end – Reliability on tolerances	– Energy saving – Plant safety – Flexibility
Low		– Energy savings	– Selectivity on waste streams	

[1] Threshold requirement
[2] Driven by raw material and energy cost for processing

Figure 1 Industry needs that can be addressed by PI

The potential benefits of PI that have been identified are significant:

- PETCHEM: Higher overall energy efficiency – 5% (10-20 years), 20% (30-40 years)
- FINEPHARM: Overall cost reduction (and related energy savings due to higher raw material yield) – 20% (5-10 years), 50% (10-15 years)
- INFOOD:
  - Higher energy efficiency in water removal – 25% (5-10 years), 75% (10-15 years)
  - Lower costs through intensified processes throughout the value chain – 30% (10 years), 60% (30-40 years)
- CONFOOD: Higher energy efficiency in preservation process – 10-15% (10 years), 30-40% (40 years)
  - Through capacity increase – 60% (40 years)
  - Through move from batch to continuous processes – 30% (40 years)

The realization of the promises of PI will require endeavors varying from technical R&D to up-scaling and industrialization.

Fundamental/strategic research

Several PI technologies can potentially be very beneficial, but still require an important fundamental/strategic research effort to reach proof-of-concept at the lab scale.

Applied research, up-scaling, industrialization

Several other novel PI technologies have been implemented for a limited number of applications. Further applied research is necessary for a wider implementation of these technologies. Prerequisites to this include the financing and development of industrial scale prototypes, and piloting facilities (when possible on existing production lines) must be made available. The skill of designing PI equipment on an industrial scale (materials, robustness, economics) is lacking, and needs to be developed.

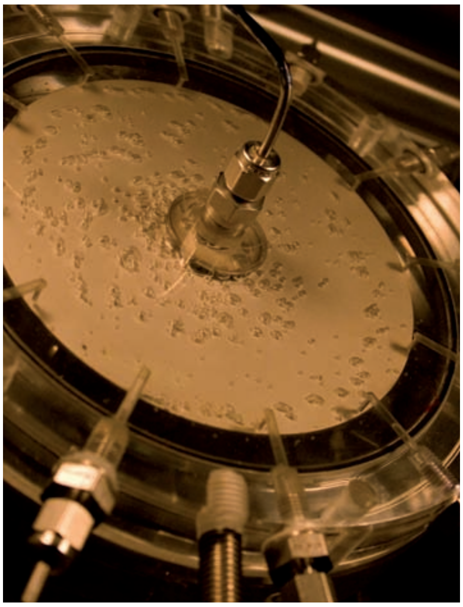


Figure 2 Spinning Disc Reactor (Courtesy of Eindhoven University of Technology)

Enabling technologies

For the successful industrial implementation of PI technologies, the following enabling technologies need to be developed for all sectors:

- Process analytical technology: (In situ) measurement and analysis methods to better understanding of kinetic and thermodynamic characteristics of chemical processes at the molecular level

- Numerical process modeling: Faster, more robust, often non-linear numerical modeling of chemical reactions
- Process control systems that can cope with the incorporation of (often continuous) PI modules in (often batch) processes.

Value chain optimization

All sectors can reap the benefits of chain optimizations enabled by novel PI technologies. Such chain optimizations often require a socio/economic paradigm shift, and call for optimization studies along the value chain as well as the development of longer-term transition paths. In the INFOOD sector, for instance, milk separation into water, proteins and fats can be conducted on-site (i.e. at the farm) with low energy-consuming micro separators. Product transportation to and handling at the factory can be limited to the relevant components, proteins and fat, saving energy and reducing CO_2 emissions by avoiding the unnecessary transportation of water and its removal at the factory.

Knowledge dissemination

In all Roadmaps, and in particular those of INFOOD and CONFOOD, limited PI knowledge and know-how were named as chief barriers. These barriers should be tackled through broad execution of Quick Scans and other knowledge dissemination activities like seminars, trainings and the communication drive behind the PI Roadmap.

The significant promise of PI calls for an extensive European PI program that will initiate and coordinate activities, involving all stakeholders that can contribute

Figure 3 Three High-Gravity Rotating Packed Bed reactors for CaCO3 nanoparticles production with capacity of 10,000 tons/a (Courtesy of Research Center of the Ministry of Education for High Gravity Engineering & Technology, Beijing)

and/or benefit from PI. The main challenge for such a program would be encouraging activities that have been developed by the industry sectors, and that fall within the wide bounds outlined above. Its success would largely depend on careful bundling of activities in cross-sector programs, and on strong coordination along the innovation value chain.

The next step in the development of a European PI program is the development of a PI Program Plan in consultation with the FP7 program of the European Union. The plan will bundle activities – as listed in the PI Roadmap – into main program lines. The content of each of the program lines will be determined by the prospective industry and knowledge infrastructure partners. An outline of these program lines will be the basis for the program; an illustrative example of outlines of such program lines is provided in Figure 4.

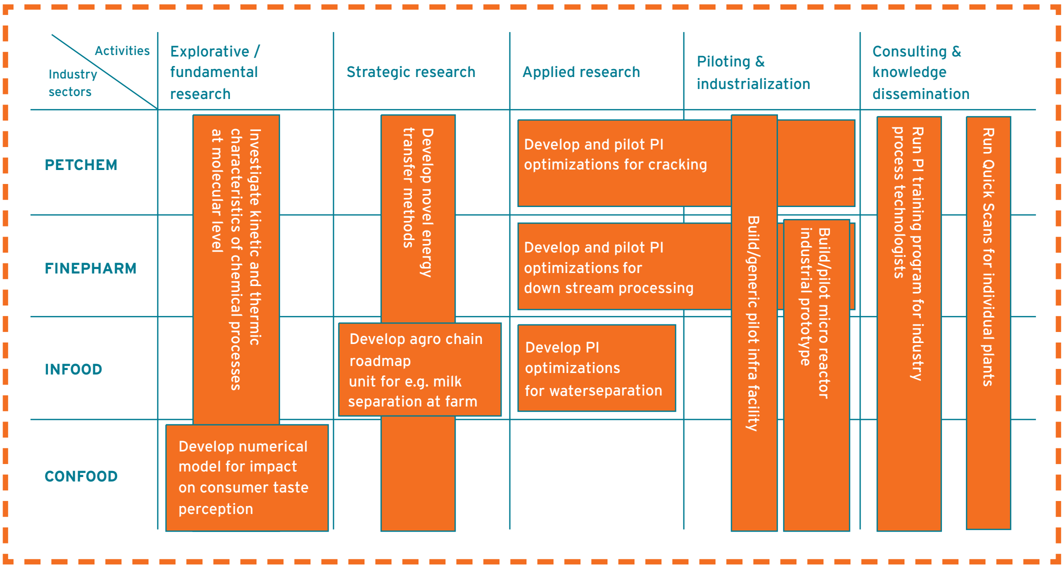


Figure 4 Programming PI activities – Illustrative

In 2008, the Action Group PI will focus on building consortia for the programming and execution of the European PI program. The industry sector teams that have developed the sector roadmaps could play a pivotal role in the development of these consortia. When the Program Plan is finalized, and sufficient commitment gathered, financing requests will be submitted to the most appropriate financing sources depending on the character of each activity – ranging from government subsidies and European grants to bank loans and venture capital funds.

At the beginning of 2008, the PI Roadmap should be communicated to all potential participants and other stakeholders. The PI Roadmap is the result of about a year's study and documentation and thus reflects state-of-the-art knowledge in the year 2007. Over the course of 2008, the PI Roadmap should be updated to further investigate benefits in value chain optimizations, and to incorporate long term development of new products and processes.

FOREWORD

We, as members of the Senior Advisory Board, are proud to present the European Roadmap for Process Intensification, which reviews the state-of the-art of Process Intensification (PI), identifies opportunities in the Dutch and European process industry and recommends concrete actions.

The development and implementation of PI has seen a worldwide acceleration in recent years. Though PI technologies sometimes reinvent conventional unit operations in an innovative fashion, they more often use novel equipment or processing methods such as multifunctional reactors, micro reactors, alternative energy forms, etc. Recent developments in views on the climate and energy supply support the need for faster and broader application of innovative PI-technologies.

Scientists from all over the world have reported on the state-of-the-art of PI technologies, and the PI Roadmap offers a valuable review of these technologies. Representatives from the Dutch process industry (petrochemicals, bulk chemicals, specialty chemicals, pharmaceuticals and food) have worked together to project this technological future onto industry needs. The results demonstrate that, apart from energy savings and CO_2 emissions reduction, PI can offer important other benefits like cost savings, selectivity improvements, lead time reduction and safety improvement. In the PI Roadmap, concrete actions are recommended for achieving these goals.

We are happy to have received significant support, both financial and in working force, from industry, the knowledge sector and the Dutch government. Without this support, the Roadmap would not have been realized. Particular support has been provided by the Dutch chemical industry through VNCI representation. PI is key to reaching the long term sustainability objectives of the chemical industry, and is part of the Business Plan which has been presented by Regiegroep Chemie. Further support from ProcessNet (DECHEMA/VDI - Fachsektion Prozessintensivierung), the European Federation of Chemical Engineering (Working Party on Process Intensification), the European Technology Platform for Sustainable Chemistry (SusChem) and Société Française de Génie des Procédés is kindly acknowledged

We are confident that the recommendations outlined by this PI Roadmap will lead to effective cooperation in 2008 between the Dutch and European process industries and knowledge infrastructures.

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A. INTRODUCTION

A study in 2006 demonstrated that PI offers important opportunities to modernize the Dutch process industry (oil refinery, petrochemicals, bulk chemicals, specialty chemicals, pharmaceuticals and food). Substantial savings are possible over time (energy, CO_2 emissions, waste production, etc.). Under the Dutch policy for Energy Transition (towards a sustainable energy system), the Platform for Chain Efficiency has initiated a roadmap for Process Intensification ("PI Roadmap") with the objectives to accelerate the introduction of PI in the Dutch process industry and to achieve a 20% reduction in energy consumption by 2050 through PI implementation alone. This PI Roadmap is at the same time part of the Business Plan for Innovation of the Chemical Industry, which has been presented in July 2007 by the "Regiegroep Chemie".

It should be stressed upfront that no roadmap is a static document, but that a roadmap is meant to be dynamic and used as such. This PI Roadmap is the result of about a year's study and documentation and thus reflects the state-of-the-art knowledge in the year 2007. It is the starting point for future activities, including regular updates to the Roadmap itself, and the programming of activities to prepare for and enable PI implementation in the process industry.

Figure A1 SMXL™ multi-tube static mixer heat exchanger (Courtesy of Sulzer Chemtech)

The project team Action Group PI, or AG PI, which reports to the Dutch Energy Initiative, started in Q4, 2006. The following activities were executed:

1. Facts & Figures

The state-of-the-art of PI worldwide has been identified through questionnaires to 70 experts, identifying patents (approximately 1,000), and a complete search for scientific publications including translation of Chinese and Japanese work. 72 PI technologies have been identified, of which 46 technologies have been described by globally-acknowledged experts in full "technology reports". A description of these 72 technologies, and a review of the 46 reports by three Dutch experts can be found in Appendix 1. Details are kept in a dedicated database which can be accessed through TU Delft and ECN.

2. Quick Scans

VNCI has approached all it's members to perform a so-called "Quick Scan" in order to identify the PI potential in specific plants. The "Quick Scan" methodology was developed by DSM, and we are pleased that DSM has granted the Dutch process industry the benefit from this methodology. 15 Quick Scans have been executed so far, 25 Quick Scans will be carried out by February 2008, and the objective is to have all Dutch chemical companies perform a Quick Scan by the end of 2008. The results of the Quick Scans will be incorporated in an update of the PI Roadmap that will be published in the course of 2008.

Figure A2 Kenics® static mixer (Courtesy of Chemineer)

3. PI Roadmap

The first step in building the PI Roadmap was to ascertain industry needs that can be addressed by PI. Promising PI technologies have been selected and the barriers to their implementation identified. Several technology roadmaps were built, specifying the necessary actions and potential benefits. Sector teams have worked on the PI Roadmap for four industry sectors: Large volume petrochemicals (PETCHEM), specialty chemicals and pharmaceuticals (FINEPHARM), food ingredients (INFOOD) and consumer foods (CONFOOD). We expect that the oil refining sector will contribute to the PI Roadmap update in the course of 2008. In some instances, the developed roadmaps just focus on existing processes and products. Possible optimizations throughout the value chain could not always be evaluated, simply because it is extremely difficult to design a complete picture of the industry 40-50 years from now. Value chains are quickly changing due to new enabling technologies including PI. It is for this reason that the PI Roadmap should remain a dynamic document, with the first addition required in 2008.

During the development of the Roadmap, the Chairman and members of AG PI communicated extensively with many stakeholders and professional organizations in the Netherlands and Europe, particularly Germany. Individual informative meetings (e.g. with VNO-NCW, MKB-Nederland, VNCI), participation in official scientific meetings, keynote lectures at conferences and informative presentations for PI-µ-React, DSTI, PIN-NL, FHI (PPA day), the European Technology Platform for Sustainable Chemistry (SusChem), ProcessNet (DECHEMA/VDI - Fachsektion Prozessintensivierung), the European Federation of Chemical Engineering (Working Party on Process Intensification) and Société Française de Génie des Procédés, and many more made sure that stakeholders were well informed. This PI Roadmap is at the same time part of the Business Plan for Innovation of the Chemical Industry, which has been presented in July 2007 by the "Regiegroep Chemie". The stakeholders in the project are depicted in Figure X.

The PI Roadmap recommends several critical activities that need to be undertaken for the acceleration of PI implementation. The report is also an informative manual for any process technologist who wants to enhance his/her knowledge on process

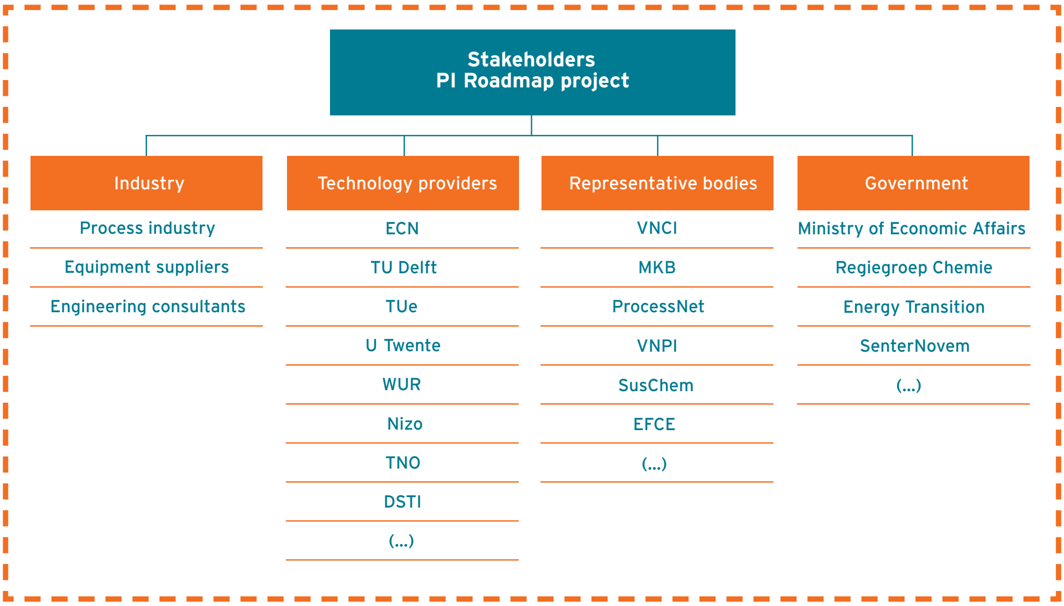


Figure A3 Stakeholders in the PI Roadmap project

intensification technologies, and wants to use PI for the optimization of his/her production process. We hope that the publication of the PI Roadmap will initiate accelerated PI implementation in many production plants in the Dutch and European process industries.

Action Group Process Intensification

- Prof. dr. Hans de Wit - Former CTO Corus, former member of the TNO Board
- Dr. ir. Arend de Groot – ECN
- Ir. Frank van der Pas – SenterNovem
- Prof. dr. ir. Andrzej Stankiewicz – TU Delft
- Ir. Willem de Vries – SenterNovem
- Dr. Hartmut Schoenmakers (Associate member) – BASF, member of the Steering Board of Fachsektion Prozessintensivierung (DECHEMA-VDI ProcessNet)

- Ir. Dick Venderbos – Former Chairman
- Marten Japenga – Former member

B. INDUSTRY NEEDS AND BARRIERS TO PI IMPLEMENTATION

Process intensification can address several needs of the process industry: cost competitiveness, energy savings[1], CO_2 emissions reduction, process safety and reliability, sustainability, and more. In the following sections, the industry needs are specified by sector, and the main barriers to PI implementation described.

Industry needs

Process intensification can address several needs of the process industry, and these needs vary considerably between sectors (see Figure B1):

Importance to sector	PETCHEM	FINEPHARM	INFOOD	CONFOOD

High	– Energy savings
	– Cost competitiveness
	– Safety
	– Regulation
		– Selectivity
		– Cost competitiveness
		– Sustainability
		– Lead time
			– Cost competitiveness [2]	– Cost competitiveness
				  – Yield
				  – Line availability
				– Product quality
				– Food safety
				– Product functionality

Medium	– Social impact – Reliability [1]	– Safety [1] – Reliability [1]	– Selectivity on end – Reliability on tolerances	– Energy saving – Plant safety – Flexibility
Low		– Energy savings	– Selectivity on waste streams	

[1] Threshold requirement
[2] Driven by raw material and energy cost for processing

Figure B1 Industry needs that can be addressed by PI

- In the PETCHEM sector, energy typically accounts for a significant part of total delivered product costs. Along side cost reductions, the reduction of CO_2 emissions is also an important need. Energy efficiency can significantly impact the cost competitiveness and sustainability of the PETCHEM sector. Safety and reliability of the process is currently at acceptable levels, so these needs are simply threshold requirements for PI introduction. PI can also lead to smaller process plants, positively affecting societal perceptions

1 Oil price locked at USD 100 per barrel

- In the FINEPHARM sector, the days of highly profitable blockbusters are over.
- Cost competitiveness in production has therefore become a very important objective, and PI can address this need by:
  - Increasing the selectivity of reactions, and thus the material yield
  - Reducing the lead time of the entire production process
- While energy costs do not account for a large part of total product costs in the FINEPHARM sector, achieving above cost reduction and material yield goals will also lead to savings in energy consumption and contribute to related sustainability needs. Safety and reliability of the process have acceptable levels today and are again a threshold requirement
- The INFOOD sector with its agro-based production is characterized by large volumes of diluted streams. Processing is constrained by the limited stability of the crops and derived materials. Cost competitiveness is dominated by energy costs for processing and waste costs, and both costs can be tackled with Process Intensification provided that potential optimizations are studied and implemented throughout the complete agro value chain.

- In the CONFOOD sector, market circumstances demand constant cost awareness which can be translated into process technology improvements for higher yields and product line availability. Product quality and food safety are important factors to consider in relation to consumer and regulatory fluctuations. Consumer food companies need continuous product innovation in order to keep up with consumer trends and changing demand. This aim translates practically into the need for process technology to increase product functionalities. Energy efficiency increases, plant safety and flexibility are seen as somewhat important needs. Energy consumption is not a major cost component, however rising energy prices will induce companies to consider savings.

Figure B2 Mobile pulse combustion dryer with evaporation capacity of 2000 kg water/hr (courtesy of Pulse Drying Systems, Inc., Portland, OR, USA)

From the Quick Scans that were executed in 2005/2006 it appeared that chemical companies expect important benefits from PI: the expected potential of PI on the short term was evaluated as "significant" in 30% of the cases, and "average" in an other 30% of the cases, for the long term these percentages were respectively 40% and 60%.

Main barriers to PI implementation

The four sectors are confronted by common barriers to rapid implementation of Process Intensification. Many promising PI technologies still require additional fundamental and applied research, and several PI technologies (e.g. micro reactors, impinging stream reactors) have achieved proof-of-concept on a lab scale and are awaiting industrialization. Some PI technologies have already been implemented. The industrialization of PI is faced with several barriers:

- Insufficient PI knowledge and know-how among process technologists
- No pilot facilities or possibilities to pilot on existing production lines
- High (technical and financial) risk of development of first industrial prototype
- High (technical and financial) risk of first implementation (retrofitting) of PI modules in existing production lines/plants
- Insufficient awareness of potential benefits of PI technologies at the management level
- Process control systems not geared to control novel PI modules

Figure B3 Fluid division mixer (Courtesy of Maelstrom Advanced Process Technologies Ltd.)

The INFOOD sector in particular requires a reassessment of the value chain to reflect its ever-dynamic landscape. Intense cooperation during and after reassessment is not easy but essential for the successful implementation of PI.

C. PI TECHNOLOGY

Definition

The definition of Process Intensification as an area of chemical and process engineering changed over the years. In early definitions, plant miniaturization was often emphasized. Obviously, miniaturization is a hallmark of Process Intensification. Equipment miniaturization significantly increases safety of chemical processes. Smaller is safer: with smaller inventories, many disastrous accidents in the chemical industry could have been avoided (e.g. Bhopal).

Process Intensification is not only about miniaturization and safety. It also has sustainability-related dimensions: reducing costs, energy consumption, material usage and waste generation. Producing much more with much less – a drastic efficiency increase – is the key to Process Intensification.

To this end, the following working definition of Process Intensification has been adopted by the Roadmap and is used throughout this document:

Process Intensification provides radically innovative principles ("paradigm shift") in process and equipment design which can benefit (often with more than a factor two) process and chain efficiency, capital and operating expenses, quality, wastes, process safety and more.

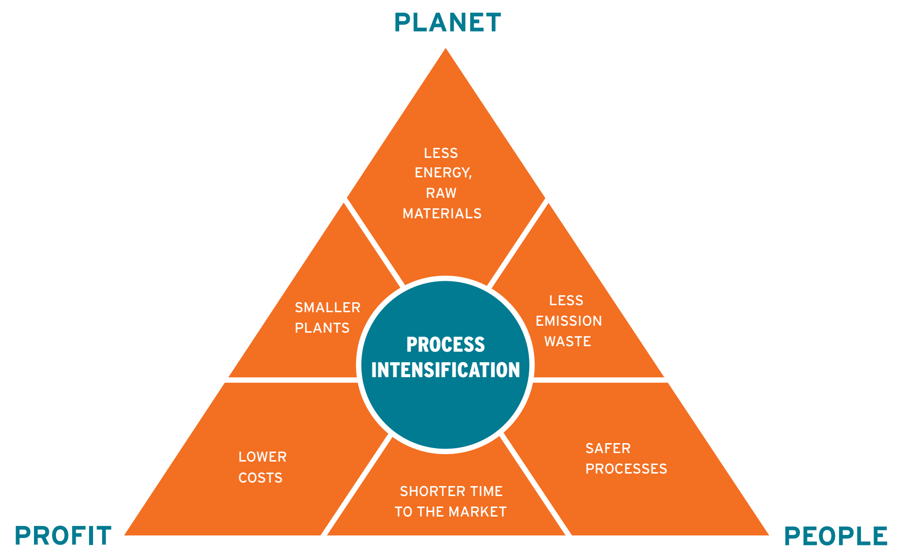


Figure C1 Process Intensification benefits align perfectly with the "Triple-P" philosophy of sustainable business

Within Process Intensification, two basic categories of technologies can be distinguished: "hardware" technologies (i.e. novel equipment) and "software" technologies (i.e. new processing methods), as depicted in Figure C2.

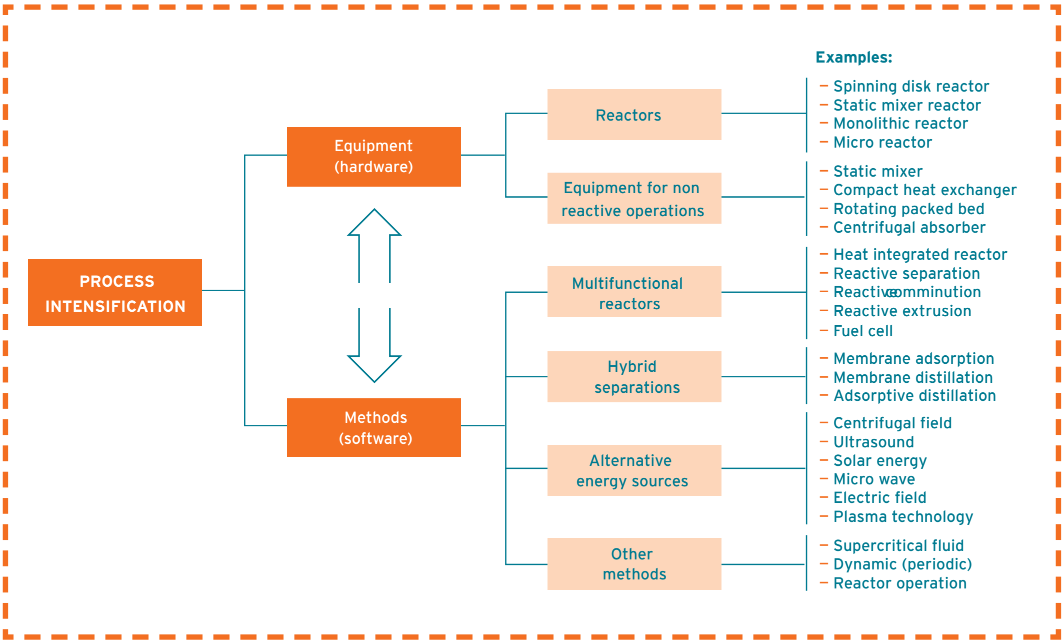


Figure C2 Elements of Process Intensification

The European Roadmap of Process Intensification has identified 72 equipment types and processing methods as PI technologies. They are listed and briefly described in Appendix 1.

It is important to realize that Process Intensification differs essentially in character from Process Systems Engineering and Process Optimization. Figure C3 briefly compares the basic features of these three areas of chemical and process engineering.

	Process Optimization	Process Systems Engineering	Process Intensification
Aim	Performance improvement of existing concepts	Multi-scale integration of existing and new concepts	Development of new concepts of process steps and equipment
Focus	Model, numerical method	Model, software	Experiment, phenomenon, interphase
Interdisciplinarity	Weak (interface with applied mathematics)	Modest (mostly applied mathematics and informatics, chemistry)	Strong (chemistry & catalysis, applied physics, mechanical engineering, materials science, electronics, etc.)

Figure C3 Basic features of three areas of chemical and process engineering

Scientific Fundament

Process Intensification is driven by four generic principles:
- Maximize the effectiveness of intra and intermolecular events
- Give each molecule the same processing experience
- Optimize the driving forces on every scale and maximize the specific areas to which those driving forces apply
- Maximize the synergistic effects from events and partial processes

Process Intensification is scientifically founded on four areas:
- STRUCTURE (spatial domain)
- ENERGY (thermodynamic domain)
- SYNERGY (functional domain)
- TIME (temporal domain)

The most relevant issues addressed by PI in each of these areas are presented in Figure C4.

STRUCTURE Spatial Domain	ENERGY Thermodynamic Domain	SYNERGY Functional Domain	TIME Temporal Domain
• Structure in molecular events • Structure in catalysts • Structure in phase contracting • Structure in transport phenomena	• Bringing energy to molecules (what form and how) • Bringing energy to catalysts • Energy transfer in hydrodynamics, mixing and transport processes • Energy management in reactors and separation systems	• Synergy on molecular scale • Synergy in transport processes • Synergy in processing units - multifunctional reactors and separators	• Timing of events • Applying dynamics • Special process control

Figure C4 Generic areas of PI

REVIEW OF 47 PROCESS INTENSIFICATION TECHNOLOGIES

Introduction

Process Intensification has developed quickly in recent years. There is no doubt that it generates creative innovations. The most recent developments in the cost of raw materials (energy and steel) will further increase the need for technologies that minimize the energy and capital costs of the processes. These PI technologies often combine processing methods in an innovative fashion, sometimes using novel equipment or methods. Surprisingly, while some of these technologies are common practice in one industry, their application in other industries may be absent. We believe that this is mainly due to a lack of awareness and, in some sectors, a lack of expertise. Recent worldwide developments in energy costs and climate awareness support the need for faster and broader application of innovative PI technologies.

Prof. Hans de Wit, in his capacity as PI Project Leader, platform Chain Efficiency, has invited us to review, on a personal basis, the available Technology Reports (kept in a dedicated database) and in particular the “Expert Brief Final Judgment” provided by the experts, attached to each Technology Report, with the objective to enable access to the wealth of data.

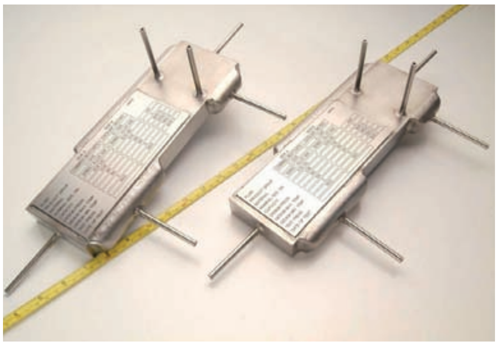


Figure C5 Compact mixer and reactor used in the manufacturing of dyes (Courtesy of Heatric)

Results

In a first approach to find commonality between the various PI Technologies, a matrix was constructed listing the technologies considered, their general benefits and challenges and barriers to implementation. This is presented in Technology matrix 1 in Appendix 1.

In a second approach, we qualitatively described the benefits and state of development of the technologies, defined the main action party to bring the technology towards application and briefly summarized for each technology the potential benefits of and barriers to implementation. These descriptions (“assessments per reported technology”) are shown in Figure C7. Necessarily, these descriptions are to some extent colored by personal bias. While this approach gives some measure of the potential of a specific technology and the possible timescale for its application, it must be realized that a technology in itself has only limited value; value may be created by applying a specific technology to a specific problem and for that reason we have refrained from ranking the technologies in order of importance or relevance. No doubt, each of the described technologies offers a unique solution for an identified problem. This has been undertaken by the Sector Teams in Appendix 2.

The attention of the Sector Teams is focused on those technologies that can be applied within a short timeframe by inserting them in current processes. However, due attention must also be paid to those ideas which are still in an early stage of definition but, once further developed, may offer tempting opportunities for new process routes in the future. Our advice to those advocating early ideas for at present unproven technologies is to link them as soon as possible to promising industrial applications in order to get focus and gain support.

Conclusions

Many of the technologies described in the 47 Technology reports offer great potential for improving the competitiveness of the Dutch process industry. While the attachments to this review are useful, there is no shortcut for defining improvement opportunities. In order to do that successfully, practitioners in the field of process technology, both in industry and academia, are strongly encouraged to get access to the available Technology Reports and reflect on its applicability in their own area of expertise/responsibility. Based on such reviews, specific opportunities for Process Intensification can be identified.

The Sector Teams have built their Sector PI Roadmaps using this review of the PI Technologies. For the PI Technologies that have become part of these roadmaps, the Sector Teams have further specified the specific barriers that need to be resolved for their sector and suggest further actions to be taken to accomplish this.

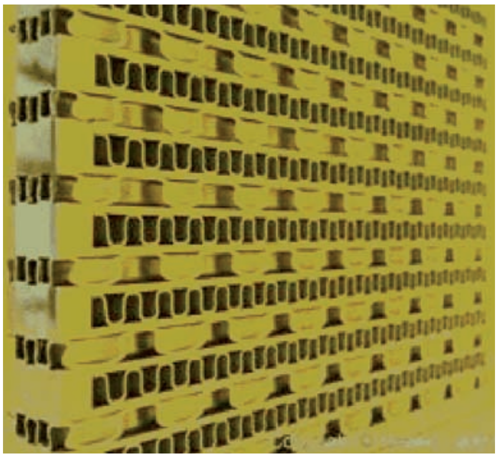


Figure C6 DBX matrix heat exchanger (Courtesy of Heatric)

The Technology matrix 2 attached in Appendix 1 shows the main benefits and barriers. A common barrier is "unfamiliarity with or lack of knowledge of PI technologies". It is our conclusion that the wide distribution among process technologists of the final PI Roadmap report will be a first step in addressing this barrier.

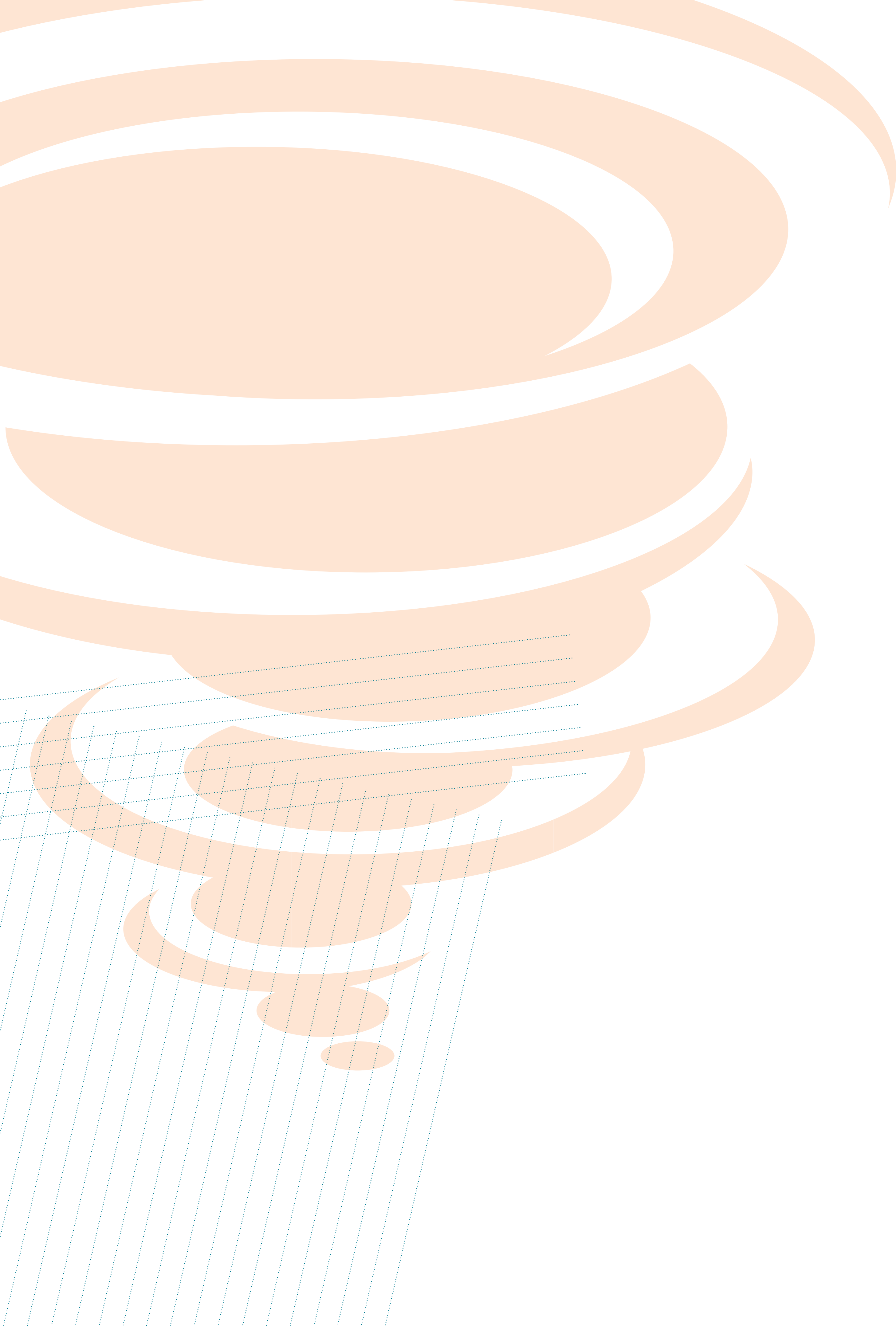
Jacob Moulijn
Fons Meijs
Ben Stouthamer

		Criteria A			Criteria B			Criteria C	Criteria D
Technology code	technology name	Potential for energy savings	Potential for eco impact CO_2	Potential to improve cost competitiveness	Ripeness application in X years	Ripeness related technology fields	likelyness of overcoming barriers	potential for inovative high qual products	Character required R&D: fundamental/ combined/applied
1.1.1	Advanced plate-type heat exchangers	medium	medium	high	<5	high	high	low	applied
1.1.2	Advanced shell & tube type heat exchangers	medium	medium	medium	<5	high	high	low	applied
1.1.4	Static mixers	medium	medium	medium	<5	medium	medium	low	applied
1.2.1.1	Heterogeneously catalyzed solid foam reactors	low	low	low	5-10	high	high	medium	fundamental
1.2.1.2	Monolithic reactors	medium	medium	medium	5-10	high	high	high	applied
1.2.1.3	Millisecond (gauze) reactors	low	low	medium	5-10	medium	medium	low	combination
1.2.1.4	Structured reactors	medium	medium	medium	5-10	medium	medium	low	applied
1.2.2	Micro channel reactors	low	low	low	>15	medium	medium	high	fundamental
1.2.3	Membrane reactors (non-selective)	low	low	low	>15	low	low	medium	fundamental
1.2.4	Static mixer reactors for continuous reactions	high	high	medium	5-10	high	high	medium	applied
2.1.1	Adsorptive distillation	medium	medium	low	10-15	low	low	medium	fundamental
2.1.3	Extractive distillation	medium	low	low	5-10	medium	medium	medium	fundamental
2.1.4	Heat-integrated distillation	high	high	high	<5	high	high	low	applied
2.1.5.3	Membrane crystallization technnology	medium	medium	medium	10-15	low	low	high	fundamental
2.1.5.4	Membrane distillation technology	medium	medium	medium	5-10	medium	medium	medium	combination
2.1.5.5	Distillation-Pervaporization	medium	medium	medium	<5	high	medium	medium	combination
2.2.1	HEX reactors	low	low	high	5-10	high	medium	high	applied
2.2.3.1	Simulated Moving Bed reactors	low	low	low	5-10	medium	medium	high	combination
2.2.3.2	Rotating Annular Chromatographic reactors	low	low	high	10-15	medium	medium	high	fundamental
2.2.3.3	Gas-Solid-Solid Trickle Flow reactors	low	low	high	10-15	high	low	medium	fundamental
2.2.5	Reactive extraction columns, HT and HS	medium	medium	low	5-10	medium	high	medium	combination
2.2.6	Reactive absorption	high	high	low	<5	high	high	medium	applied
2.2.8.1	Reactive distillation	high	high	high	<5	high	high	medium	applied
2.2.8.2	Membrane-assisted reactive distillation	high	high	high	5-10	high	medium	high	applied

Figure C7a General overview of the PI Technology reviews

		Criteria A			Criteria B			Criteria C	Criteria D
Technology code	technology name	Potential for energy savings	Potential for eco impact CO_2	Potential to improve cost competitiveness	Ripeness application in X years	Ripeness related technology fields	likelyness of overcoming barriers	potential for inovative high qual products	Character required R&D: fundamental/combined/applied
3.1.2	Centrifugal liquid-liquid contractors	high	medium	medium	<5	high	high	low	applied
3.1.3	Rotating packed beds	medium	medium	high	5-10	high	medium	medium	combination
3.1.4	Rotor stator devices	high	medium	medium	<5	high	high	high	applied
3.2.2	Hydrodynamic cavitation reactors	medium	low	medium	10-15	medium	medium	medium	fundamental
3.2.3	Impinging streams reactor	medium	low	medium	<5	high	medium	low	applied
3.2.4	Pulsed compression reactor	high	high	medium	>15	low	low	medium	fundamental
3.2.5	Sonochemical reactors (ultrasound and low frequency sonics)	medium	low	medium	10-15	medium	medium	medium	fundamental
3.2.6	Ultrasound enhanced crystallization	medium	low	medium	10-15	low	low	medium	fundamental
3.2.7	Ultrasound reactors for enhanced distingration/phase dispersion/ mass transfer	medium	medium	medium	<5	high	high	medium	applied
3.2.8	Supersonic Gas-Liquid reactors	low	low	low	<5	high	high	low	applied
3.3.1.1	Electric field-enhanced extraction	high	low	low	<5	high	high	low	combination
3.3.2	Induction and ohmic heating	low	low	high	5-10	medium	medium	high	combination
3.3.3.1/2	Microwave heating/microwave drying	high	low	high	<5	high	high	high	applied
3.3.3.4.1	Microwave reactors for non-catalytic and homogeneously catalyzed liquid phase process	low	low	low	10-15	medium	low	medium	fundamental
3.3.3.4.2	Microwave reactors for heterogeneously catalyzed chemical processes	low	medium	high	10-15	high	medium	high	combination
3.3.3.4.3	Microwave reactors for polymerization reactors and polymer processing	low	low	low	10-15	medium	low	high	fundamental
3.3.4	Photochemical	high	medium	medium	10-15	medium	medium	medium	fundamental
3.3.5	Plasma (GlidArc) reactors	low	low	medium	5-10	medium	medium	medium	combination
4.1.1	Oscillatory	medium	low	high	<5	high	high	low	combination
4.1.2	Reverse flow reactor operation	medium	high	medium	5-10	medium	high	medium	combination
4.1.4	Pulse combustion drying	medium	low	medium	5-10	low	medium	high	combination
5.1.2	Supercritical separations	medium	high	high	<5	medium	high	medium	combination

Figure C7b General overview of the PI Technology reviews (continued)



D. PI ROADMAP

Roadmaps for the implementation of PI in each sector have been developed. Alongside summaries of each roadmap, an overview of potential benefits and recommended actions is also included here.

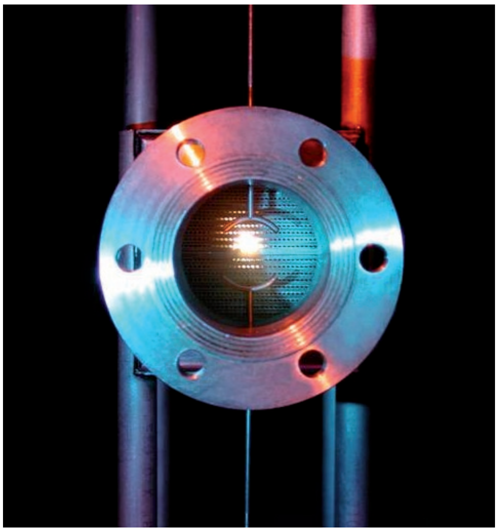


Figure D1 Diesel microstructured steam reformer (Courtesy of Institut für Mikrotechnik Mainz)

Utilized technologies

A wide range of PI technologies has been selected as technologies which have the potential to meet the needs of the industry. In particular, two main streams of PI applications have been identified:

- PI innovations for *reactors* (e.g. micro reactors, monolith reactors, spinning disc reactors, reactive separations) can be applied in all sectors
- PI technologies for more efficient *energy transfer* (e.g. ultrasound, pulse, plasma, microwave) can achieve more focused and selective heating for all sectors

A complete overview of technologies identified by each roadmap is provided in Appendix 1.

Potential benefits of PI

For each roadmap, potential benefits have been formulated for the short/mid term (5-10 years) and the long term (30-40 years). These benefits should not be interpreted as industry commitment to reach these targets, but rather as a target to be used to plan relevant actions. The potential benefits of PI that have been identified in the sector roadmaps are significant:

- PETCHEM: Higher overall energy efficiency – 5% (10-20 years), 20% (30-40 years)
- FINEPHARM: Overall cost reduction (and related energy savings due to higher raw material yield) – 20% (5-10 years), 50% (10-15 years)
- INFOOD:
  - Higher energy efficiency in water removal – 25% (5-10 years), 75% (10-15 years)
  - Lower costs through intensified processes throughout the value chain – 30% (10 years), 60% (30-40 years)
- CONFOOD: Higher energy efficiency in preservation process – 10-15% (10 years), 30-40% (40 years)
  - Through capacity increase – 60% (40 years)
  - Through move from batch to continuous processes – 30% (40 years)

PI also has important potential benefits in other process industries, like paper/pulp, steel, and others. As an example, a roadmap for process intensification for the steel industry, developed by CORUS, is included in Appendix 2.

Recommended actions

The realization of the full potential of PI will require endeavors varying from technical R&D to up-scaling and industrialization.

Fundamental/strategic research

From the technology review and the roadmaps, it can be concluded that several PI technologies offer important potential, but require important fundamental/strategic research in order to reach proof-of-concept on the lab scale. These PI technologies are:

- Foam reactors
- Monolith reactors
- Micro reactors
- Membrane reactors
- Membrane absorption/stripping
- Membrane adsorption
- HEX reactors
- Reactive extraction
- Reactive extrusion
- Rotating packed beds
- Rotor-stator mixers
- Spinning disc reactors

Figure D2 ART ® Plate Reactor
(Courtesy of Alfa Laval)

Applied research, up-scaling, industrialization

Several other novel PI technologies have already been implemented for a limited number of applications. Further applied research is necessary for broad implementation of these technologies. Prerequisites to this include the financing and development of industrial scale prototypes, and piloting facilities (when possible on existing production lines) must be made available. The skill of designing PI equipment on an industrial scale (materials, robustness, economics) is lacking, and needs to be developed. For the following PI technologies, efforts for industrialization can begin:

- Plate, plate-fin, plate-and-shell, flat tube-and-fin heat exchangers
- Static mixer reactors
- Membrane extraction
- Reactive absorption
- Reactive distillation
- Centrifugal extractors

Enabling technologies

For the successful industrial implementation of PI technologies, the following enabling technologies need to be developed for all sectors:

- Process analytical technology: (In situ) measurement and analysis methods to better understanding of kinetic and thermodynamic characteristics of chemical processes at the molecular level
- Numerical process modeling: Faster, more robust, often non-linear numerical modeling of chemical reactions
- Process control systems that can cope with the incorporation of (often continuous) PI modules in (often batch) processes.

Value chain optimization

All sectors can reap the benefits of chain optimizations enabled by novel PI technologies. Such chain optimizations often require a socio/economic paradigm shift, and call for optimization studies along the value chain as well as the development of longer-term transition paths. In the INFOOD sector, for instance, milk separation into water, proteins and fats can be conducted on-site (i.e. at the farm) with low energy-consuming micro separators. Product transportation to and handling at the factory can be limited to the relevant components, proteins and fat, saving energy and reducing CO_2 emissions by avoiding the unnecessary transportation of water and its removal at the factory.

Knowledge dissemination

In all Roadmaps, and in particular those of INFOOD and CONFOOD, limited PI knowledge and know-how were named as chief barriers. These barriers should be tackled through broad execution of Quick Scans and other knowledge dissemination activities like seminars, trainings and the PR and marketing drive behind the Roadmaps.

PETCHEM SECTOR PI ROADMAP – EXECUTIVE SUMMARY

Ambitious targets have been set for energy efficiency improvements at the national as well as European levels. Process Intensification (PI) can play an important role in achieving these targets. In August 2007, the Petrochemicals sector team (PETCHEM) began to develop a PI roadmap for this sector. The roadmap focuses primarily on energy efficiency improvements.

Approach to the assessment of PI potential

- The overall needs of the PETCHEM sector were determined. Alongside energy savings, safety, cost competitiveness, reliability and CO_2 emissions reductions are important needs which can be addressed by PI. PI can also lead to smaller plants and therefore more positive social impact
- The chemical processes were arranged in five categories, including the major energy consumers: ethylene cracking and ammonia. Roadmaps for each of these categories were developed. For some processes, a specific roadmap was developed as an example

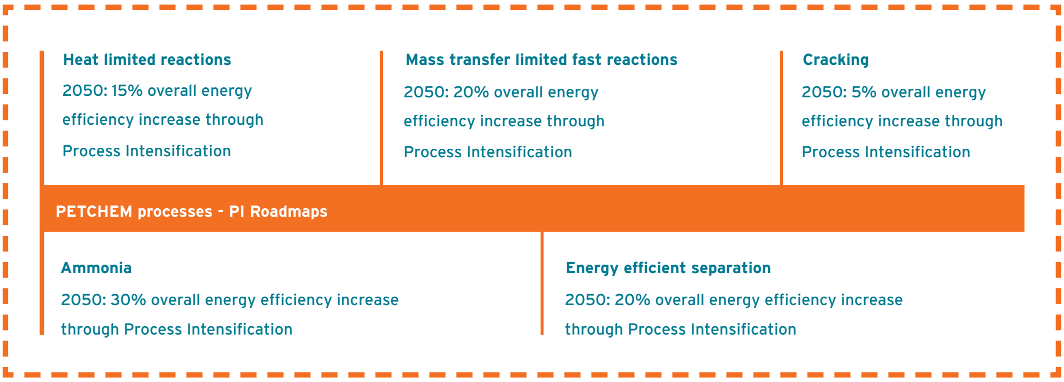


Figure D2 Objectives of PI Roadmaps for PETCHEM sector

- The process needs of each of the five categories were compared to a list of about 60 promising and well-defined or documented PI technologies. Improvement potential within the next 10-40 years was then assessed
- Given the limited timeframe in which the roadmaps had to be developed, a number of boundaries were set. The scope was narrowed down to existing equipment and processes and did not include other new process ideas in the product chain. The limited operating window set in many cases by the catalyst was also assumed as a boundary. Process synthesis studies leading to new process concepts have also not been included in the scope. Finding combinations of processes and upgrading byproducts with PI technologies were only discussed in some cases. Bio-based processes, which are likely to play a substantial role in our product portfolio 20 years from now, were also not included. Most attention was focused within the 10-20 years timeframe, therefore a 2050 vision was seldom given
- PI aims to realize innovation, creating technology breakthroughs for these processes. Various kinds of barriers will be encountered. Addressing these barriers and suggesting solutions for overcoming them were among the main objectives of the team

Processes and barriers

Figure D3 presents an overview of the processes, their percentages of overall energy consumption in the chemical industry and the roadmap to which each process belongs.

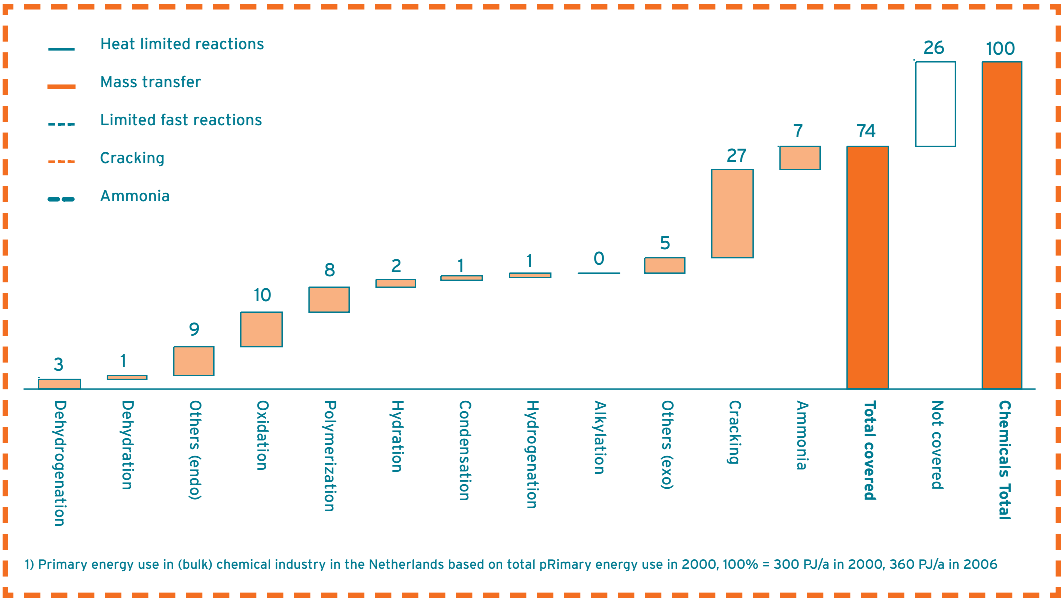


Figure D3 Energy consumption covered by PI Roadmaps [% of total energy consumption1)]

The chemical industry has already achieved substantial improvements in energy efficiency, and in some cases the limits of current facilities seem to be close to thermodynamic minima. Given the large size of this industry and the highly competitive market in which it operates, reliability in combination with predictability are key to achieving a low cost position. Unexpected production interruptions have serious impacts on operational and logistic costs, which can rapidly erode margins. New technologies or concepts are therefore always scrutinized against an array of factors.

Other barriers to PI implementation are:
- High cost to retrofit PI technologies in current plants
- Risks of commercializing breakthrough technology
- Scale-up of PI
- Lack of PI knowledge, unfamiliarity with PI technologies
- Long development path
- IP cooperation during R&D

The benefits of PI

The benefits of PI can be extensive and diverse, from energy efficiency improvement to lower capital needs for investments, from safety improvements to space savings. The participating members of the sector team have issued status reports on the progress of PI within their companies. These reports can be accessed through TU Delft and ECN. So far, most companies have implemented only a few PI projects. They are investigating other PI opportunities, such as divided wall columns and combined reaction-separation.

Participating members of the sector team have estimated the energy efficiency improvements that PI promises:

- With an overall long-term 2050 energy efficiency improvement target of 50%, we envision that PI can contribute 20% in absolute terms, i.e. 40% of the target energy savings
- Based on this roadmap exercise, a reduction potential of 10% (in absolute terms) has been identified for the existing processes. This figure may be as much as 80% for specific processes
- To achieve the 20% reduction goal, development of new technologies and implementation of these technologies in all areas (e.g. new processes, bio-based routes) will have to occur. It should be noted that definitions (what falls under PI), technologies and situations will evolve over time
- The path forward for PI
- The NW European area is home to the strongest chemical cluster in the world. PI offers enormous opportunities for this cluster to maintain a competitive leadership position.
- To achieve the envisioned 20% reduction, we strongly advocate taking advantage of the momentum that the roadmapping process has built by moving forward on these concrete actions:
- Initiate a (limited) number of research initiatives around the technological barriers to promising energy efficiency improvements (e.g. hybrid reactors)
- Establish a long-term commitment from all stakeholders to implement PI: industry, government and knowledge infrastructure
- Initiate accelerated knowledge transfer about the development and implementation of PI
- Create shared piloting and/or scale-up facilities
- Ensure efficient coordination of new initiatives around PI, catalysts, separation, biotechnology, etc. These activities should be incorporated in the Sustainable Covenant that is being developed for the chemical industry
- Update the PI roadmap in December 2008 with:
  - Broadened scope of process evaluations in which other parts of the product chain (i.e. outside battery limits) are included as well
  - Explored PI potential for new sustainable processes (e.g. based on bio feedstock)
  - Evaluated results of the quick scans that are being executed by all VNCI members in 2007/2008

Significant input from VNCI members has been provided over the last four months. The sector team and Roland Berger Strategy Consultants have spent considerable effort to prepare this PI roadmap. The PETCHEM sector team would like to thank all those who have contributed to its development.

PETCHEM sector team

- Hans Feenstra – Akzo Nobel (chairman)
- Peter Alderliesten – ECN
- Peter Arnoldy – Shell
- Frits Hesselink – Lyondell
- Michiel Schenk – DOW
- Hans Veenenbos – VNCI
- Hans de Wit – Action Group PI

FINEPHARM SECTOR PI ROADMAP – EXECUTIVE SUMMARY

Industry needs

In the fine chemicals and pharmaceuticals industry, the days of highly profitable blockbusters are over. Cost competitiveness in production has therefore become a very important objective and can be achieved through:

- Increasing the selectivity of reactions, and thus the material yield and sustainability. Today, the typical selectivity of chemical reactions is 80%; PI technologies can lead to a typical selectivity of 90%. For a typical multi-step process, this can lead to an increase in material yield from 30% to 60%, which also contributes to the sustainability of the processes
- Reducing the lead time of the entire production process. Current processes typically have up to 50 process steps, with a lead time (i.e. the time between the delivery of the raw materials until the completion of the product) of several months. Moving to integrated and continuous process steps, combined with a process design based on thorough understanding of the chemistry, will reduce these lead times considerably

Other needs of the FINECHEM sector are presented in Figure D4 below. While energy costs do not account for a large part of total product costs in the FINEPHARM sector, achieving above cost reduction goals will also lead to a 50% savings in energy consumption and contribute to related sustainability needs. Safety and reliability of the processes are currently at acceptable levels, and the implementation of PI should not lead to lower levels.

General barriers

- Suppliers for industrial applications of PI technologies are lacking, as the industrial design and piloting of novel PI equipment is expensive and technologically uncertain
- The capital cost of PI modules per production capacity today is often higher than that of traditional reactors. By developing lower cost PI reactors in which the production of multiple products can be combined, the capital cost barrier can be addressed (see Figure D5)

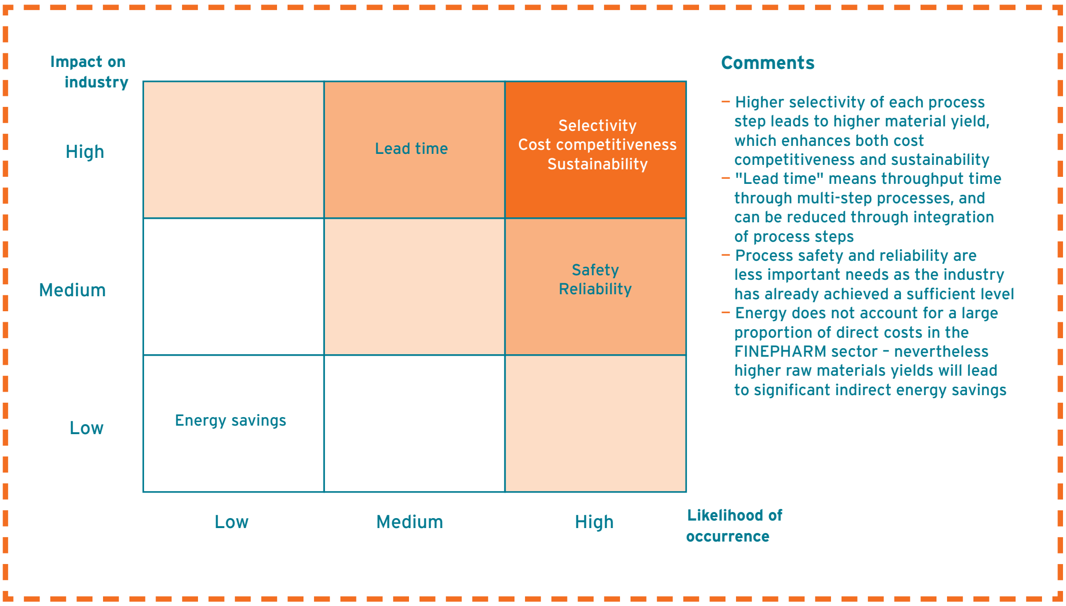


Figure D4 Overall needs of the FINEPHARM sector

- Solutions for Down Stream Processing, in combination with PI reactors, hardly exist
- For step-change improvements in the efficiency of chemical reactions, a thorough understanding of the kinetic and thermodynamic characteristics at a molecular level is necessary – this knowledge does not currently exist

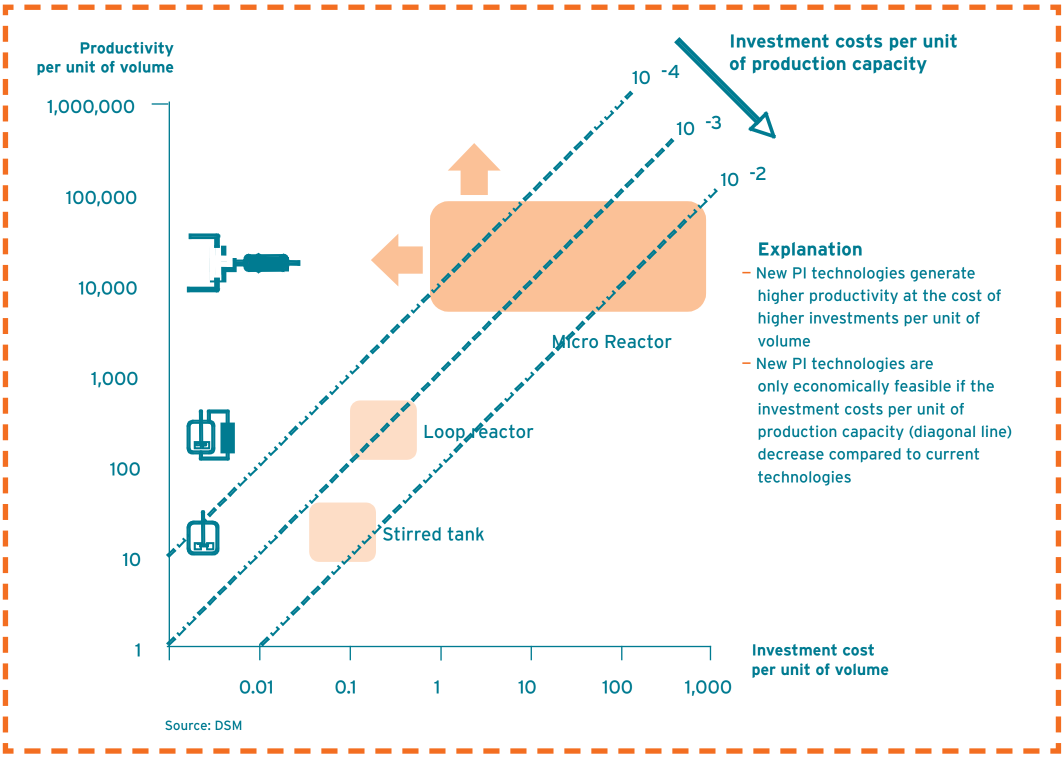


Figure D5 Economic evaluation of Micro Reactors

FINEPHARM Roadmap

A multipurpose serial production train, using PI technologies, can result in 50% reduction of production costs within 10-15 years. This vision can be achieved through the PI roadmap for FINEPHARM, as described in Figure X.

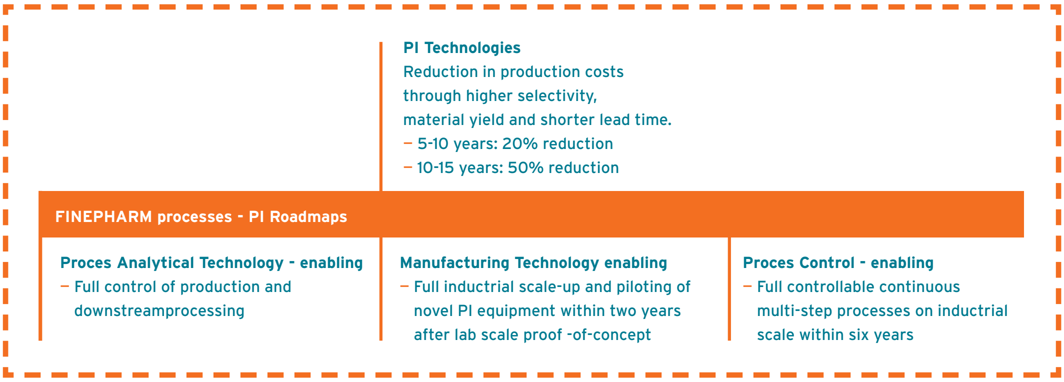


Figure D6 Objectives of PI Roadmaps for FINEPHARM sector

To achieve this vision, PI technologies that today have been proven on a laboratory scale need to be scaled-up and industrialized. Furthermore, several alternative heat-transfer PI technologies have (longer term) potential, and need to be proven through laboratory testing and fundamental research. In the field of micro reactors in particular, Dutch know-how is increasingly recognized worldwide (see Figure X).

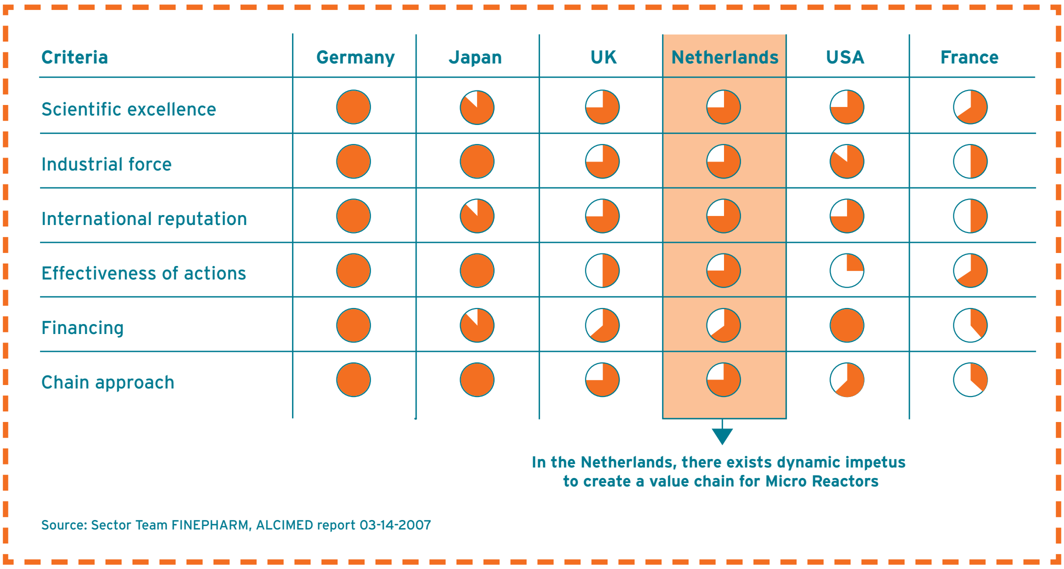


Figure D7 Comparison of micro reactor development in selected countries

For the implementation of PI technologies, the development of the following enabling technologies is vital:

- Process Analytical Technology: A thorough understanding of the kinetic and thermodynamic characteristics of reactions at a molecular level is necessary. This knowledge does not currently exist, and is indispensable for the successful implementation of PI. On-line analytical techniques for monitoring and validating continuous processes also need to be developed
- Manufacturing Technology: For many PI technologies, clinical scale proof-of-concept has been developed. The challenge now is to realize industrialization
- Process Control Technology: For the coupling of PI modules into production series where other process steps (still) remain batch, we need to develop reliable process modeling and control systems

FINEPHARM sector team

- Arij van Berkel – TNO
- Frans Kaspersen – NV Organon, part of Schering Plough Corporation
- Gert Lagerweij – Solvay
- Raf Reintjes – DSM Pharmaceutical Products
- Jaap Schouten – TUe
- John van der Schaaf – TUe

INFOOD SECTOR PI ROADMAP – EXECUTIVE SUMMARY

Industry needs

The INFOOD sector has very specific needs for the development of its technology base. The agro-based production in this sector is characterized by large volumes of diluted streams. The production chain and processing is constrained by the limited stability of crops and derived materials. Crops with short storage limits such as milk, sugar beets and potatoes present particular challenges.

This sector of raw materials has intrinsic links to land usage, crop quota and direct needs to utilize various chains in processing. The chain begins with land, crop or farm, it continues into transportation, factory processing, refining and later in the derivatization processes of the agro materials. The needs of this sector are outlined in Figure D8.

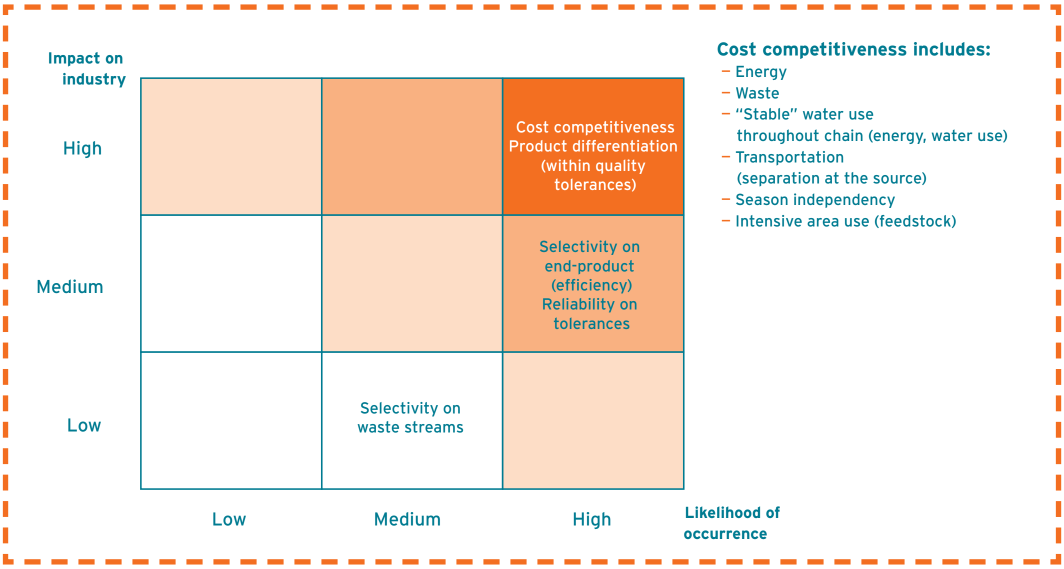


Figure D8 Overall needs of the INFOOD sector

These include:

– The cost competitiveness that is dominated by energy costs for processing and waste reduction. The limited availability of crops drives optimization of yield and extensive valorization; otherwise, the bio-based industries in the Netherlands can no longer compete
– The product differentiation by quality must stay within narrow specifications. This is only partly achieved by continuous operation. Quality is strongly affected by the variability of the agro material due to source and seasonality

Apart from these intrinsic aspects, the rise of crops dedicated for bio-ethanol and bio-diesel will compete for valuable land and will require intensified crops, land usage and process approaches (e.g. bio refineries).

PI can achieve many optimizations, provided these are studied and implemented throughout the agro value chain. Examples include:

– Separation in (or close to) the field of crop components, water, minerals and remaining soil can lead to important energy and transportation cost savings
– Preservation of crop components (immediately) after harvesting can eliminate the seasonality effect, leading to much higher capacity utilization of process equipment and related capital costs
– Valorization of non-food crop components into bio-fuels can be achieved through new crop and harvesting technologies

General barriers

An important barrier to PI implementation in this sector is the limited availability of process experts. Current process experts focus on optimizing existing plants with no attention paid to new, green field-designed factories. This focus has led to negative impressions of PI in the INFOOD sector. In practice, new, PI-based technologies are difficult to incorporate in existing factories. This leaves limited room for adopting new technologies and PI concepts in particular.

PI technology relevance for INFOOD

Several new promising technologies have been identified which are outlined in the roadmaps and in the "relevance matrix" in Appendix 2. However, many technologies must be tested by both equipment manufacturers and agro process experts before scaling up. The Netherlands currently lack the required scale and collaboration.

INFOOD Roadmaps

The INFOOD sector team developed 3 PI Roadmaps, of which the objectives are presented in Figure D9. The CONFOOD sector team made 2 PI Roadmaps (for "capacity increase" and "batch to continuous") which are also very relevant for the INFOOD sector.

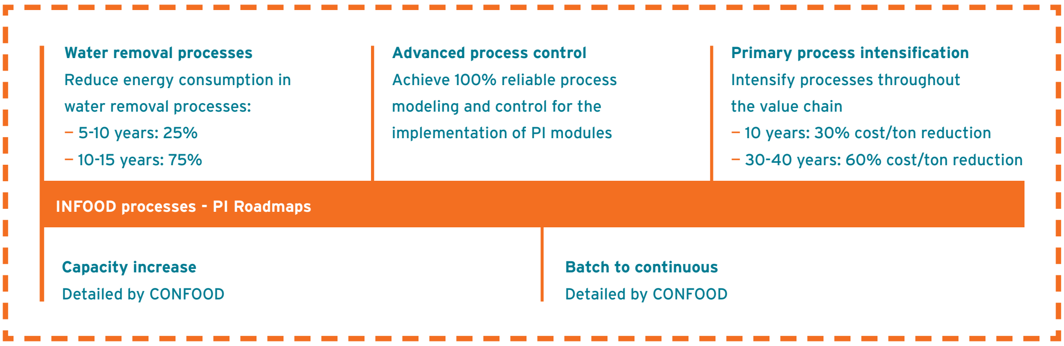


Figure D9 Objectives of PI Roadmaps for INFOOD sector

These roadmaps are a first snapshot at the processes which lie within the scope of the represented companies. We strongly recommend that in 2008, a larger group of agro representatives should extend this roadmap with related chain-oriented aspects of the sector and address future product and process developments.

INFOOD sector team

- Jan Maarten de Bruijn - Suikerunie
- Marco Giuseppin – Avebe
- Andor Hendriks – DMV
- Gabrie Meesters – DSM
- Johan Sanders – WUR

CONFOOD SECTOR PI ROADMAP – EXECUTIVE SUMMARY

Industry needs

The consumer food sector has specific needs with regards to its products and processes. Market circumstances require constant cost awareness which can be translated into process technology improvements for higher yields and product line availability. Product quality and food safety are very important factors to consider in relation to consumer and regulatory demands. Consumer food companies depend on continuous product innovations in order to keep up with consumer trends and changing demand. This effort is translated in the need for process technology to increase product functionalities. Energy efficiency increases, plant safety and flexibility are seen as somewhat important needs. Energy consumption is not a major cost component, however rising energy prices will force companies to consider savings. The needs are summarized in Figure D10 below.

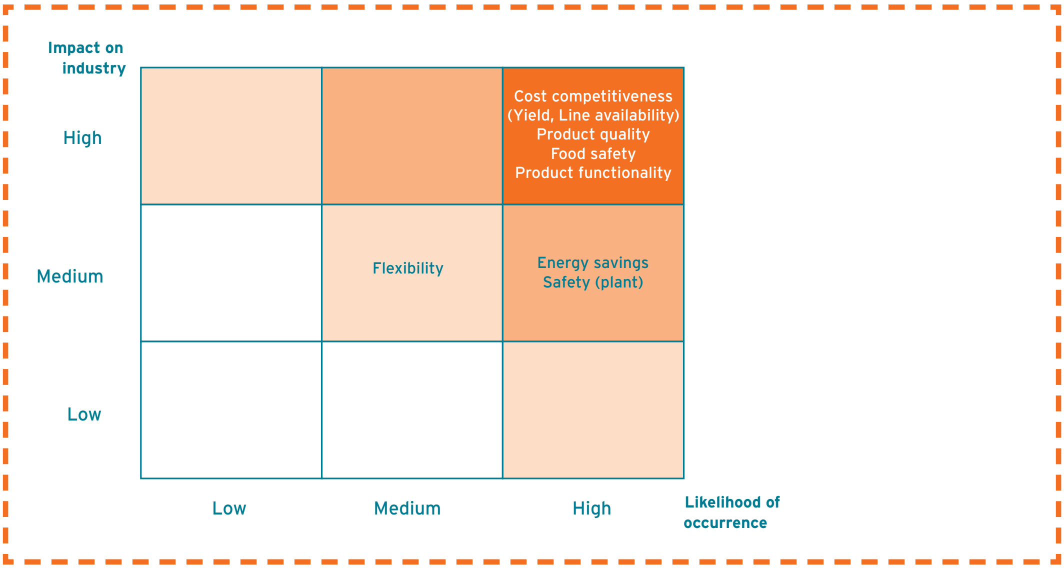


Figure D10 Overall needs of the CONFOOD sector

It is important to stress that for the CONFOOD sector, energy savings are important but are not the major drivers of the businesses. There are more paramount goals in terms of reducing conversion costs: product quality and product functionality. These attributes, however, are strongly and indirectly linked to energy savings (e.g. improved yield directly contributes to less energy usage per product).

PI technology relevance for CONFOOD

PI technologies have been reviewed for their technical potential in the CONFOOD sector. An overview is presented in Appendix 2.

General barriers

To realize the potential of PI technologies in the CONFOOD sector, a number of generic barriers need to be tackled:

- Food regulation is highly limiting process innovation, PI implementation included. Procedures to adjust production processes, very specific regulatory requirements and quality validation processes could be improved to stimulate process innovation

- Many food products include higher viscosity products or even (semi) dry products. This is an aspect which is clearly different from the more mainstream PI area in the chemical industry
- The CONFOOD sector often deals with sensitive materials (e.g. sensitive to heat, shear) which prevents the sector from working in very extreme process conditions
- As reliability is an important aspect in food production, R&D programs tend to be long and costly and extensive piloting is required. Pilot facilities are limited and mainly available for small scale production. Improved piloting facilities would clearly be beneficial for PI implementation and reduce R&D lead time and costs
- Developed and proven technologies need to be produced on an industrial scale. Current plant and equipment manufacturers are reluctant because of limited market potential for specific technologies. Furthermore, few equipment manufacturers are available in the Netherlands. Larger scale technology application will push PI implementation in food production forward

CONFOOD Roadmaps

A number of technologies have been identified to have high potential for the CONFOOD area. For the most relevant application fields, roadmaps have been developed to structure and visualize expected development times for each of the technologies and the potential energy savings. See Figure D11.

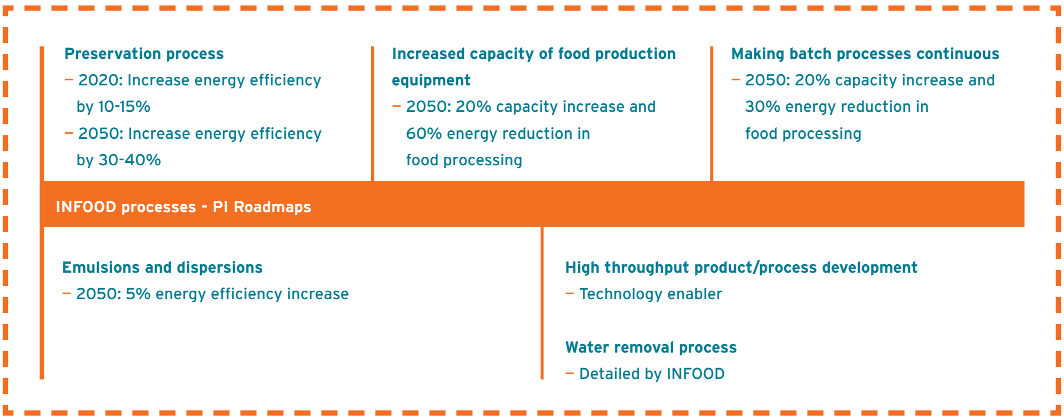


Figure D11 Objectives of PI Roadmaps for CONFOOD sector

Preservation

The following developments will result in an overall energy efficiency increase of 30-40%:

- Milder techniques leading to better product quality
- More selective treatment of ingredients
- More effective removal of micro traces and
- Increased processing flexibility (e.g. less cleaning after batch run)

Increased capacity of food product equipment

Reduction of (bio)fouling in food processing equipment and an increase in cleaning efficiency will result in a 20% capacity increase and a 60% energy reduction in food processing.

Continuous fermentation of food products

The following developments will result in a 20% capacity increase and a 30% energy reduction:

- More constant quality of fermented products
- More effective heating or cooling and mixing
- Higher yields
- Higher production capacity
- Simultaneous oxidation and fermentation

Emulsions & dispersions

Higher efficiency, smaller particles and smaller particle size distribution will result in an overall energy efficiency increase of 5%.

High throughput product/process development is considered a technology enabler for all roadmaps and will not result in stand-alone energy efficiency increase. For efficient drying, the INFOOD roadmap on water removal processes is also highly relevant for the consumer food industry.

The roadmaps presented in this report are a first step towards PI within the consumer food sector. Starting in 2008, the CONFOOD sector should begin to develop improved piloting facilities and ways to cooperate with industry partners and equipment manufacturers on actual development of PI technologies on an industrial scale.

CONFOOD sector team

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E. NEXT STEPS

The PI Roadmap demonstrates that the benefits of PI for the process industry can be significant in terms of cost competitiveness, energy savings and sustainability. Only a broad action plan can ensure the fast and successful implementation of PI. The actions required are not limited to technological R&D alone; piloting, up-scaling and industrial implementation of PI technologies are extremely difficult hurdles. Action which encompasses both societal and economic factors is required to build more awareness and knowledge of PI, and to provide the right incentives to the process industry to start using PI on a large scale (see Figure E1).

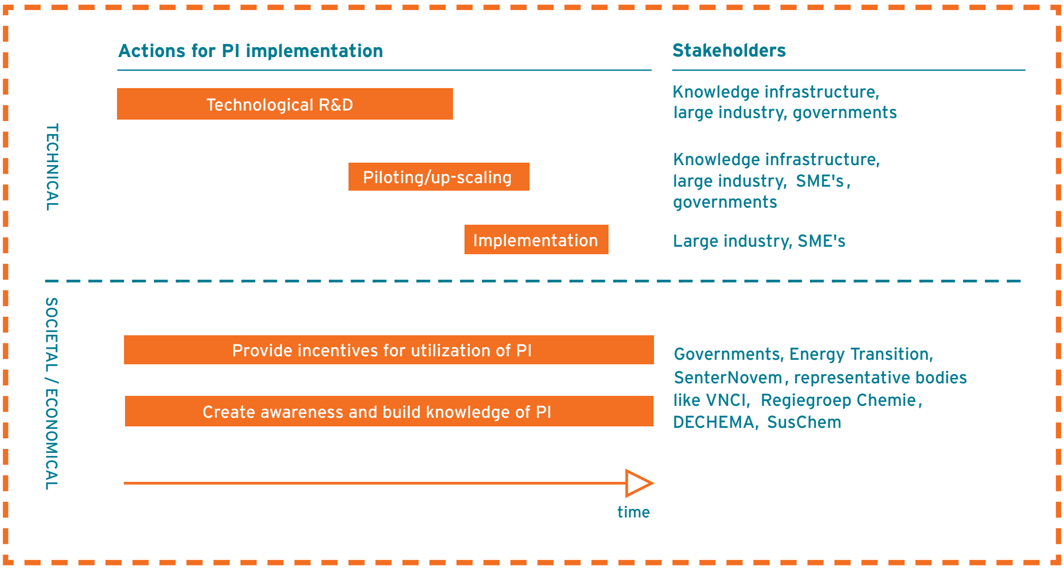

Figure E1 Required actions for implementation of PI

The significant promise of PI calls for an extensive European PI program that will initiate and coordinate activities, involving all stakeholders that can contribute and/or benefit from PI. Such a program would oversee the following activities, which are detailed in Chapter D:

- Explorative/fundamental research
- Strategic research
- Applied research
- Piloting/up-scaling
- Consulting and knowledge dissemination

For the execution of these activities, the public and private sectors will need to form co-operations and partnerships that are best suited to the character of each activity. Industrial contribution will become larger when activities move closer to commercialization (see Figure E2).

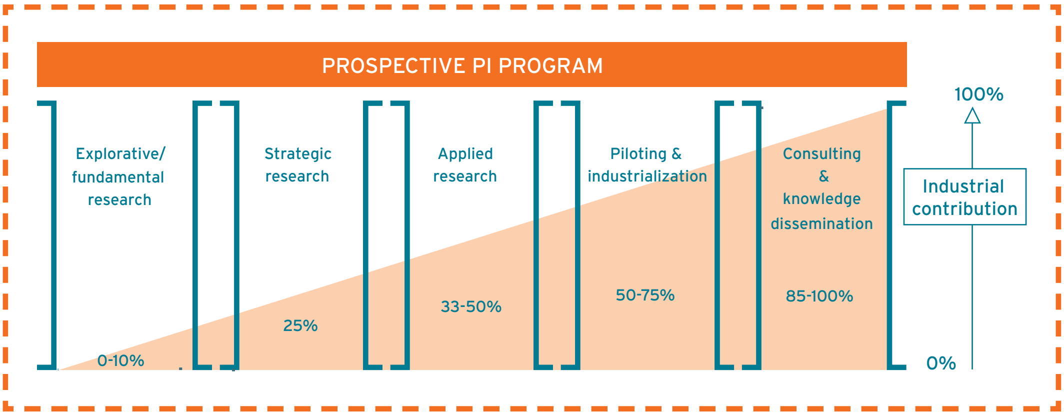

Figure E2 Concept of prospective European PI program – Activities

The main objective of the PI program will be to carefully bundling these activities in cross-sector programs, and provide a strong coordination along the innovation value chain.

The next step in the development of a European PI program is the development of a PI Program Plan in consultation with the FP7 program of the European Union. The plan would bundle activities – as listed in the PI Roadmap – into main program lines. The content of each of the program lines will be determined by the prospective industry and knowledge infrastructure partners. An outline of these program lines will be the basis for the program; an illustrative example of outlines of such program lines is provided in Figure E3.

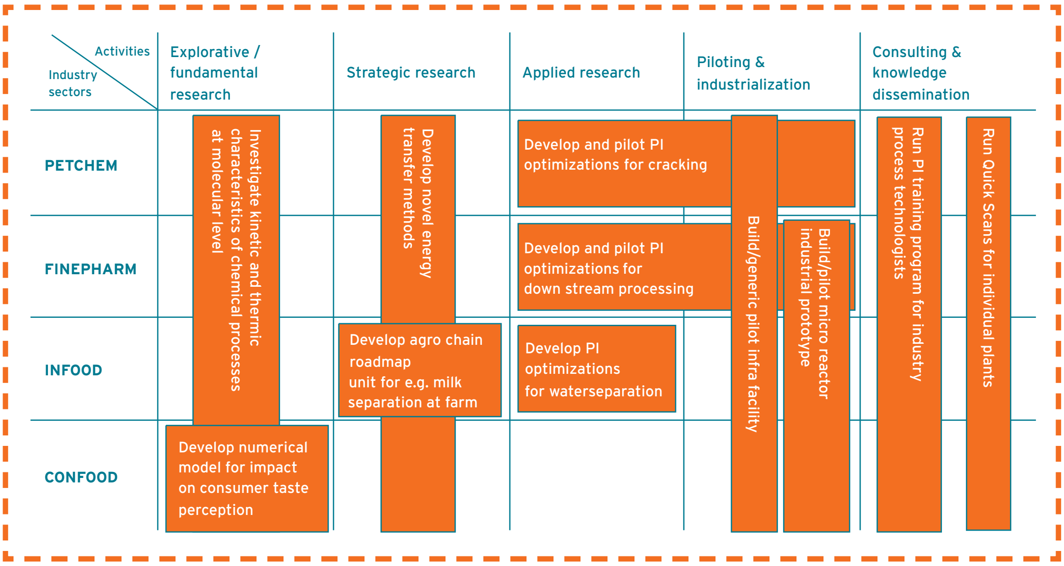

Figure E3 Programming of PI activities – Illustrative

The prospective European PI program will be virtual, the execution of its activities executed by several organizations (knowledge infrastructure, industry, government, etc.) depending on the character of the activities.

In 2008, the Action Group PI will focus on building consortia for the programming and execution of the European PI program. The industry sector teams that have developed the sector roadmaps could play a pivotal role in the development of these consortia.

From the start of 2008, the PI Roadmap should be communicated to all potential participants and stakeholders. A Program Plan should be developed for the prospective PI program in consultation with the FP7 program of the European Union. At the same time, potential participants in the program should be asked to indicate their commitment. When the Program Plan is finalized, and sufficient commitment gathered, financing requests will be submitted to the most appropriate financing sources depending on the character of each activity – ranging from government subsidies and European grants to bank loans and venture capital funds. After initial funds have been granted, an open call for projects will be organized, and the first activities of the prospective PI program should start (see Figure E4).

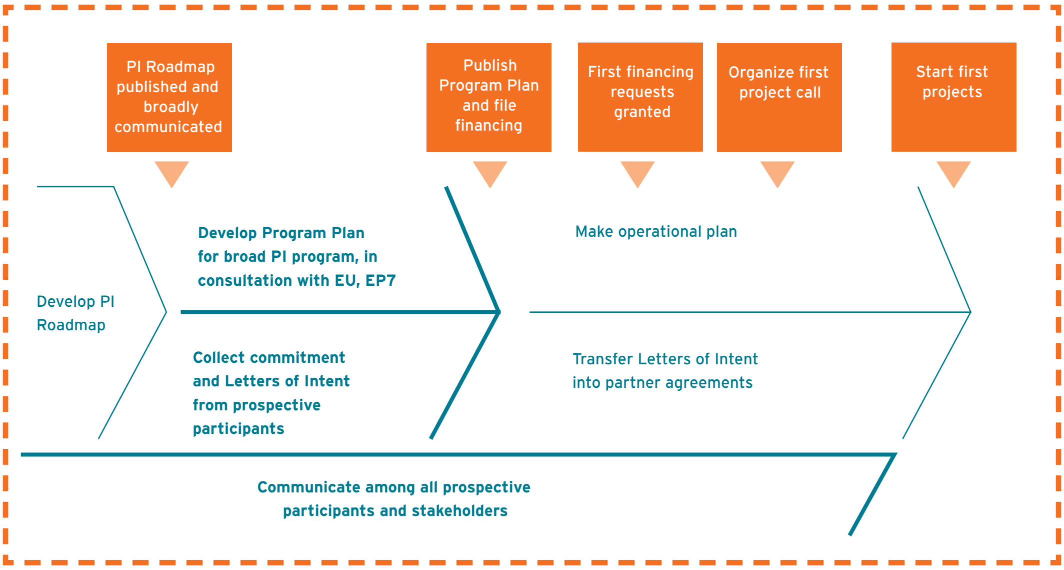

Figure E4 Next steps towards the European PI program

Over the course of 2008, the PI Roadmap should be updated to further include potential longer term (30-40 years) development of products and processes, and to investigate additional benefits in value chain optimizations.

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G. ABBREVIATIONS

AG PI	Action Group Process Intensification
CONFOOD	Consumer food sector
DECHEMA	German Society for Chemical Engineering and Biotechnology
DSP	Downstream processing
DSTI	Dutch Separation Technology Institute
ECN	Energy research Centre of the Netherlands
EFCE	European Federation of Chemical Engineering
FHI	Dutch Federation "Het Instrument", instrumentation branche
FP7	Seventh Framework Programme of the European Union
FINEPHARM	Specialty chemicals and pharmaceuticals sector
INFOOD	Food ingredients sector
MKB-Nederland	Representative body for Dutch SMEs
NIZO	Nederlands Instituut voor Zuivel Onderzoek – Food research institute
PETCHEM	Large volume petrochemicals sector
PI	Process Intensification
PIN-NL	Dutch Process Intensification Network
PI-µ-React	Consortium for development of micro reactor technology
ProcessNet	Chemical technology knowledge network, part of DECHEMA
R&D	Research & Development
SenterNovem	Agency of the Dutch Ministry of Economic Affairs, promoting sustainable development and innovation
SME	Small and Medium sized Enterprise
SusChem	European Technology Platform for Sustainable Chemistry
TNO	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek, Dutch organization for applied research
TU Delft	Delft University of Technology
Tue	Technische Universiteit Eindhoven
UTwente	University of Twente
VDI	Association of German Engineers
VNCI	Vereniging van de Nederlandse Chemische Industry, representative organization of the Dutch chemical industry
VNPI	Vereniging Nederlandse Petroleum Industrie, representative organization of the Dutch petroleum industry
VNO-NCW	Verbond van Nederlandse Ondernemingen (VNO) and Nederlands Christelijk Werkgeversverbond (NCW), representative organization of Dutch industry
WUR	Wageningen University and Research Centre

EUROPEAN ROADMAP FOR PROCESS INTENSIFICATION

Process Intensification (PI) presents a set of often radically innovative principles ("paradigm shift") in process and equipment design, which can bring significant benefits in terms of process and chain efficiency, capital and operating expenses, quality, wastes, process safety, and more.

The PI Roadmap has been developed for the following sectors: petrochemicals, bulk chemicals, specialty chemicals, pharmaceuticals, food ingredients, consumer foods. For each sector significant potential benefits from PI have been identified, for instance higher energy efficiency, cost competitiveness, raw material yield.

The realization of these potential PI benefits will require a multitude of actions, of which the character varies from technical R&D to up-scaling and industrialization:

- *Fundamental / strategic research* - Several PI technologies can potentially be very beneficial, but still require an important fundamental/strategic research effort to reach proof-of-concept at the lab scale;
- *Applied research / up-scaling / industrialization* - Several other novel PI technologies have been implemented for a limited number of applications. Further applied research is necessary for a wider implementation of these technologies. Prerequisites to this include the financing and development of industrial scale prototypes, and piloting facilities must be made available;
- *Enabling technologies* - For the successful industrial implementation of PI technologies, the following enabling technologies need to be developed for all sectors: Process analytical technology: Kinetic and thermodynamic characteristics of chemical processes are insufficiently understood at the molecular level – (in situ) measurement and analysis methods need to be developed; Numerical process modeling: faster, more robust, often non-linear numerical modeling of chemical reactions need to be developed; Process control systems need to be developed that can cope with the incorporation of (often continuous) PI modules in (often batch) processes;
- *Value chain optimization* - All sectors can reap significant benefits from chain optimizations in combination with novel PI technologies. These chain optimizations often require a socio/economic paradigm shift, call for optimization studies along the value chain and development of longer term transition paths;
- *Knowledge dissemination* – The spread of knowledge and know-how of PI should be tackled through a wide execution of the Quick Scans, and other knowledge dissemination activities like seminars, trainings, and a broad communication and distribution of the PI roadmap.

The significant potential benefits of PI call for a broad European PI program that will initiate and coordinate all the required activities, and will involve all stakeholders that can contribute and/or benefit from PI.

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