CIRCULAR ENGINEERING:

Processes and chemistry for a sustainable local industry

White paper summary

Société Française de
Génie des Procédés

SFGP

FOREWORD

Circular Engineering, a new concept in chemical engineering

Systemic approaches, mass balances, energy balances, optimization, work flow management... The concepts of circular economy integrate all of these fundamentals of chemical engineering, which is therefore naturally an essential element in the construction of this new economic model.

The circular economy aims to implement a new model of society that sorts, recycles, valorizes and optimizes stocks and flows of materials, energy and waste, and incorporates the idea of sharing flows between different users or interconnected industrial sites. However, it will only become a reality if there is a complete eco-design of the product that integrates production, subsequent use and end-of-life aspects, as well as exchanges between different production sites, so as to minimize environmental impact and meet society's commitments to sustainable and decarbonized development. Product eco-design must therefore be integrated into the eco-design of the factory, which is itself part of an industrial eco-park within a local area.

Faced with these new challenges, and in order to support a sustainable and competitive reindustrialization, the French Society of Chemical Engineering (SFGP) has decided to develop the concept of Circular Engineering for which they have produced a White Paper, a summary of which you will find here. The examples highlighted in this document are proof of the dynamics in France around this topic, demonstrating a certain maturity of approaches and concrete industrial implementations. A strong partnership between academia and industry has already been established in many areas of the circular economy. The development of new multidisciplinary skills, the association of industrial sectors, eco-design and the efforts in the field of materials engineering are opening up prospects for innovation and cost reduction, so that this potential resource can become a genuine secondary raw material. However, the necessary changes to current legislation (both at national and European levels), as well as economic and social issues, are major obstacles to this approach.

In the pages that follow, you will see how the concept of Circular Engineering enables a responsible reindustrialization that is closely connect to citizens.

François NICOL
President of the SFGP

PREFACE

The linear economy that developed with the advent of industrial mass production and consumption since the early 20th century has lifted a significant portion of the population out of poverty and extended human life expectancy. However, it has been accompanied by hyper-consumption, which has required unrestrained global production that is now leading humanity towards its ruin given the finite nature of accessible resources and the associated planetary equilibrium.

We must now reassess our current models, draw inspiration from those that have historically provided resilience and sustainability to human communities, and adapt them to today's world whilst considering the expectations of citizens, the potential future progress, and the ensemble of solutions, technologies, and sciences.

The circular economy, as envisioned for decades by pioneers like Walter Stahel, remains to be fully realized. Implementing it will require profound changes in terms of the way we consume products, notions of ownership, marketing and commercial incentives, as well as the flows and interactions among primary actors – industry to start with. Challenges such as shared usage, component reuse, "high circularity" (which encompasses enhancing the original performance of a product and intensifying its use) and material recycling must be addressed. Anticipating and adapting to these challenges requires an engineering capacity that is yet to be fully structured, particularly in the stages of design. This is why Circular Engineering should play a central role in building new models and be accompanied by strengthened expertise in this area.

In this regard, the work of the SFGP on Circular Engineering is essential for advancing the comprehensive implementation of the circular economy.

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This document is a summary of the White Paper on Circular Engineering published by the SFGP.
The full version is available on the SFGP website (www.sfgp.asso.fr)

FROM CHEMICAL ENGINEERING TO CIRCULAR ENGINEERING

Circular Engineering aims at developing engineering methods that contribute to the implementation of economical closed loop production paths – commonly referred to as the "circular economy" – for the transformation of materials.

Consequently, it is not surprising that Circular Engineering incorporates the fundamentals and paradigms of chemical engineering and chemical engineering: systemic approaches, material balances, energy balances, chemical modification of materials, flow management, modeling and optimization.

Hence, driven by evolving societal needs, the science of chemical engineering and chemical engineering has almost naturally become an essential component in the implementation and development of the circular economy.

The circular economy should enable a decrease in the use of resources and industrial impact on both resources and biodiversity, minimize waste production and limit energy consumption, all while considering economic and social equilibria.

The circular economy seeks to establish a new societal model based on sorting, recycling, valorization, reuse, optimization of raw materials and flows, energy, and waste. This model integrates the idea of sharing flows among various users or interconnected sites, industrial or not.

This is a rapidly expanding field that requires a nuanced and holistic approach. Most of the concepts in Circular Engineering stem from chemical engineering. These provide the circular economy with essential diagnostic tools and metrics related to the development of optimized processes, including the establishment of recycling channels that span most industrial sectors.

Finally, the transition from linear engineering to Circular Engineering cannot be considered without taking into account local environmental, economic and social impacts. Indeed, the soundness of circularity must be addressed in all its dimensions.

Chemical engineering activities align with the **pillars of the circular economy**, which include:

Sustainable sourcing (sustainable extraction/exploitation and procurement) concerns the way in which resources are exploited/extracted. It aims for efficient exploitation by limiting exploitation waste and environmental impacts, in particular in the exploitation of energy and mineral resources (mines and quarries) or in agriculture and forestry, for both renewable and non-renewable resources/energy. This pillar includes elements related to private and public procurement (i.e. by companies and public authorities).

Eco-design aims to minimize the environmental impact of a process, product or service by taking into account its entire life cycle from the design stage onwards.

Industrial and territorial ecology, also known as industrial symbiosis, is a way of organizing businesses through the exchange of resources and energy or the pooling of needs.

The Functional Economy favors using over owning and tends to sell services associated with products, rather than products themselves.

Responsible consumption should lead the buyer, whether an economic actor (private or public) or a citizen-consumer, to make their choice(s) by taking into account the environmental impacts at all stages of the life cycle of the product/good/service.

Extension of the period of use by the consumer leads to repair, second-hand sale or donation, or second-hand purchase in the context of reuse or reutilization.

Recycling aims to use raw materials derived from biomass or waste. Chemistry plays an essential role in characterizing these new raw materials, which are complex by nature.

The SFGP, which holds the role of animating and networking the scientific skills of chemical engineering in France, has organized its **activities in several themes**, all of which have very strong links with Circular Engineering. In November 2021, the SFGP organized the Cathala-Letort days of reflection and forecasting on Circular Engineering, the aim of which was to demonstrate the interest of chemical engineering in the context of the circular economy. The SFGP makes a clear distinction between the circular economy, which is a global and integrated interdisciplinary approach to a sustainable economy, and Circular Engineering, which is defined by the adaptation of processes, new production channels, systemic modelling, etc. Indeed, Circular Engineering should be considered as one of the major components of the circular economy.

ECOSYSTEMS, ACADEMIC AND INDUSTRIAL CHALLENGES

Ecosystems

The eco-system of the circular economy, which includes issues related to circular engineering, is now well structured in France under the leadership of the Ministry of Ecological Transition and Territorial Cohesion and the Ministry of the Economy.

Government programs and plans launched and underway (France 2030, France-Nation-Verte plan).

Funding actions led by the BPI, the ADEME and the ANR for research programs, in addition to the Horizon Europe program and the support of local (departmental, regional, conurbations and metropolitan areas) authorities. The latter have put in place specific support for public and private actors in the development of circular economy projects. Some of these initiatives are being developed as part of the France 2030 program.

Prospective and think-tank tools are proposed by associations such as the Institut national de l'économie circulaire (INEC) and the OREE association, often in collaboration with professional organisations such as FEDEREC (*Fédération des entreprises du recyclage*) and FNADE (*Fédération nationale des activités de la dépollution et de l'environnement*).

Eco-organisations such as CITEO (household packaging), Ecologic (electrical and electronic equipment wastes), *Ecosystém* (household electrical and electronic equipment), *Ecomaison* (building & construction) and *Valdelia* (building & construction) are all involved in the recycling process.

Competitiveness clusters: TEAM2, AXELERA, France-Water-Team, Bioeconomy For Change and Matéralia.

Learned societies, which are increasingly involved in the subject.

Major research organizations, which support specific programs.

Academic challenges

A survey carried out by the SFGP in 2021 shows that **academic players in chemical engineering** are very active in the field of circular engineering, with almost 20 projects underway throughout France. The common point between these projects is the high degree of multi-disciplinarity, a strong link between local territories and ecosystems, and the involvement of at least one industrial partner.

These projects concern all the pillars of the circular economy, with more pronounced actions on recycling, sustainable supply, industrial ecology, local territories and the systemic approach, social acceptability and eco-design.

In addition, education in circular engineering is growing rapidly (e.g. new European Masters BIOCEB[1], Masters ECOD[2], etc.). The current university courses are largely focused on chemical engineering tools and specialized masters.

Industrial challenges

Awareness of the need for human activities to be sustainable is now widely shared and understood, partly as a result of improved education and information, but also because the first effects of climate change and the scarcity of water and raw materials are being felt by everyone.

In our societies, which are based on strong industrial and tertiary activities, adapting to this demand of sustainability requires the **creation of a sound circular economy** and **far-reaching** changes. All activities involved in the transformation of materials are involved; there will be no sustainable circular economy if industrial and supply activities are not organized and transformed in this direction.

However, in order to move from idea to implementation, studies are needed to ensure the **coherence of organizational and investment choices** and, a certain **sustainability of the planned activities**.

These studies must lead to well-founded proposals, followed by concrete actions to reorganize flow and material processing methods.

An **eco-design of processes** must therefore be proposed and justified. This should describe the material pathways and the technical implementation of the processes. It should also define how economic, social and environmental value is created through alternate ways of organizing the different processes, most of which are yet to be designed, developed or industrialized and generalized at a large scale.

The choices to be made then need to be **explained and understood to the diverse actors** involved. A solid engineering framework, including technical studies and economic, social and environmental justification, is therefore needed to support these decisions and their subsequent implementation.

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[1] Biological and Chemical Engineering for a sustainable Bioeconomy with the implication of academics from AgroParisTech and the university of Reims-Champagne-Ardennes.

[2] Circular Economy and Sustainable Organization at Polytech Marseille.

KEY PRINCIPLES AND EXAMPLES OF APPLICATIONS OF CIRCULAR ENGINEERING

Eco-design of processes

Eco-design aims at limiting and reducing the environmental impact of processes, taking into account the economic and social balance at each stage of the life cycle. It is based on adapting **traditional tools for industrial processes and systems to the challenges of the circular economy** (modelling, data analysis, optimization, industrial ecology, machine learning, etc.).

A **multi-scale and systemic vision** must also be implemented in order to take into account models that are increasingly complex in terms of size and formulation, thus representing the complete system under study.

Finally, since the decentralized production and management of local resources promotes their valorization and the reduction of their environmental impact, the **question of the interoperability of systems** must be raised, with the aim of creating new local economic activities based on short production circuits, reuse and recycling.

Sustainable sourcing and recycling

Clothing, materials, glass, paper and cardboard, chemicals... **Recycling** or **reusing materials and waste** can significantly reduce their carbon and energy footprint.

Example: Bromine regeneration

Bromine and its derivatives, which are used in the manufacture of a wide range of chemical products, are extracted from seawater or groundwater. The extraction and associated operations have significant environmental and energy impact. *Séché Environnement* has developed an alternative technology at Saint-Vulbas (Ain) that is based on the use of bromide-rich waste coming from the pharmaceutical and chemical sectors. This process – the only one of its kind in the world – is based on the thermal purification of bromine using a static furnace. It recovers more than 99% of the bromine contained in the waste.

Meanwhile, **mineral resources** are becoming increasingly critical. Facing this threat, the circular economy can help alleviate the environmental pressures that have been exerted on these resources in recent years and reduce supply risks.

Industrial and local ecology

CO2 recycling is part of the circular carbon economy, which transforms carbon from a waste product of one industrial activity into an input product for another industrial activity.

Example: The CIMENTALGUE* project

AlgoSource Technologies develops processes for recycling CO2 from industrial sources through the cultivation of microalgae. Since 2019, it has been participating in the CIMENTALGUE project to set up a demonstrator at a cement plant in Lyon to capture CO2 from the flue gas produced during cement production. The aim of the operational program of the demonstrator (2023-2024) is to validate and optimize this concept on a representative scale by testing two different strains of microalgae.

**Coordinated by the VICAT cement group, it also involves the Total group and the University of Nantes. In addition to funding from the ADEME, it is supported by the Pays de la Loire and Auvergne-Rhône-Alpes regions. It is accredited by the Mer Bretagne Atlantique competitiveness cluster.*

Other avenues being explored by manufacturers are the **use of biomass** to replace fossil or petroleum-based products with bio-based products, and the **valorization of bio-waste in a local area**. However, the latter poses a number of chemical engineering challenges, in particular the development of flexible or adaptive processes.

Example: The iDEES* project

The aim of this project is to develop a decision support tool for choosing a sustainable organic waste management scenario for a given area (schematically: source separation without collection and individual or neighborhood micro-valorization processes versus source separation with collection and industrial valorization processes). This tool is designed to adapt environmental, economic and social assessment methods to the context of organic waste management. Potentially, it could be applied to other sectors of activity, such as plastics recycling and the production of bio-based materials and energy.

** iDEES: Integration of Environmental, Economic and Social Dimensions in a circular economy approach. The project (2023-2025) is funded by the Hauts-de-France Region and involves the Université de Technologie de Compiègne (UTC), the conurbation of Compiègne (ARC) and the Syndicat mixte du département de l'Oise (SMDO).*

Product life extension

Extending the lifetime of certain equipment through **reuse, reutilization or repair** can help conserve resources and reduce waste without resorting to costly and complex processes such as recycling.

This is exemplified by lithium-ion (Li-ion) batteries used in electric mobility. These batteries are typically removed from electric vehicles when they reach about 80% of their initial capacity. However, they can be repurposed for other applications, serving as second-life batteries in stationary storage systems until they decline to 50% or 60% of their original capacity. It is important to note that repurposing these batteries requires **careful management of risks** associated with their extraction, health assessment, storage, transportation and second-life applications.

Example: The SafeLiBatt* project

The aim of this project is to provide a scientific basis for the safe and sustainable development of second-life batteries. It identifies the risks of failure and thermal runaway of first-life and second-life batteries, assesses the environmental and socio-economic impacts, proposes integrated risk management measures and develops test protocols for second-life batteries.

** Safety concerns and opportunities related to advanced materials and new technologies in energy generation and storage. The SafeLiBatt consortium is coordinated by Boku (University of Natural Resources and Applied Life Sciences, Austria) and includes Ineris (Institut national de l'environnement industriel et des risques, France), BAM (Bundesanstalt für Materialforschung und -prüfung, Germany), Brimatech (Austria) and the Institute for Technology Assessment (Austria).*

Decarbonization and CO2

Decarbonization of industry is a key issue in the European context of 'zero carbon emissions' by 2050.

There are **many avenues for research**, most of which relate to chemical engineering: development of new processes that minimize CO2 emissions, creation of modelling and simulation tools, treatment of effluents (in particular through CO2 capture), new indicators for monitoring, assessing performance and managing industrial processes, strengthening the role of life cycle analysis and eco-conditionality criteria.

As the consumption of materials, energy and heat is inherent to industrial processes, three main levers need to be activated simultaneously or progressively to decarbonize industrial activity:
- energy efficiency, by optimizing energy sources;
- the energy mix, through electrification and the integration of low-carbon and renewable energies;
- material efficiency and recycling, by using less raw material or more recycled materials.

Water

The concept of the circular economy extends to water and its uses, whether from agricultural, industrial, domestic or urban sources. The treatment of wastewater and sludge, particularly in wastewater treatment plants, is at the heart of the issue.

Although most water treatment and sludge recovery and valorization processes already exist, the **contribution of chemical engineering** is still essential for many aspects. In particular, by:

- taking into account the specific quality criteria for treated water at the project design stage, so that that the water can be reused;
- developing water treatment processes that target emerging pollutants (e.g. chemicals, pharmaceuticals, nanoparticles, microplastics, etc.);
- reducing – or even reversing – the energy footprint of wastewater treatment plants, specifically by maximizing heat recovery and energy production from sludge;
- determining the appropriate scale for each process;
- reducing the carbon footprint of wastewater treatment plants by developing local, low-cost materials for wastewater treatment.

Energy

Unlike major material resources, energy is not 'circular' and its loss is inevitable. Within the context of the circular economy, one approach is to close the loop by converting waste into energy when material recirculation is not possible. However, this option should only be considered as a last resort. An interesting alternative is **thermal treatment** to produce an intermediate energy vector.

Renewable energies are also fully associated with Circular Engineering, however, their development poses new challenges, regarding storage and transportation in particular.

Finally, chemical engineering must play an integrative role by consolidating diverse knowledge to establish various scenarios for the evolution of energy systems and in particular, quantify and qualify the proposed solutions using reliable and indisputable indicators.

Agro-industries

Circular engineering in the agro-industry aims at the **efficient and sustainable use of all resources** – raw materials, animal and plant resources, water and energy – to provide food and non-food production with sustainable quality and in sustainable quantities, while preserving and regenerating ecosystems.

This involves increased **recycling** and **reuse** (animal feed, energy production, transformation of bio-waste into fertilizers or molecules for bio-based chemicals, etc.), **selective sorting** and the use of **biomass**. However, the use of biomass must be managed carefully to avoid competition with food production without increasing the use of inputs (which are often carbon-based) and water, and to ensure preservation of biodiversity, adaptation to climate change and the introduction new agricultural and agronomic practices.

Example: The MINIMEAU* project

The treatment and management of wastewater effluents from agri-food activities sometimes represents a heavy burden for industry and a significant loss of raw materials. The MINIMEAU project has developed several software packages for the eco-design of water networks (decision support, study and simulation of innovative treatment processes, environmental analysis of process scenarios offering potential improvement), including the possibility of recycling lightly polluted water or aqueous effluents after appropriate purification treatment. The studies carried out in the project have shown a potential reduction in water consumption of the order of 30%.

** Minimizing water consumption in agro-industries through the development of an integrated approach combining water footprint indicators and mass pinch analysis. This is a 4-year project (2018-2021) funded by the French research agency (ANR) and accredited by the HYDREOS cluster. It involves academic partners (AgroParisTech/UMR GENIAL, IRSTEA/UMR ITAP), a manufacturer (ProSim), several technical centers (CTCPA, ITERG, ACTALIA, IFV) and a technology transfer center (CRITT Paca).*

Eco-design in agricultural and agro-industrial systems primarily applies to production systems, but it can also be applied to the product-packaging ensemble.

Industrial and territorial ecology aims at creating symbioses between different human activities in order to function as an ecological system. At a local level, it aims at creating resource exchange loops for optimized management.

RECOMMENDATIONS

In conclusion to this work on Circular Engineering, the SFGP provides the following recommendations that should be rapidly implemented:

Development of systems approaches, with the creation of models to manage the transition from the linear economy to a circular economy;

Coupling life cycle analysis with process simulation, material, product and energy flow management, as well as economic analyses;

Development of multi-disciplinary approaches with the integration of human and social sciences;

Development of flexible processes that can be adapted depending on the resources used;

Determination of thermo-physical data for new resources such that reliable process models can be developed;

Development of specific sensors for advanced process control, being linked to artificial intelligence in particular;

Development of an integrated approach to economize natural resources, water (or its reuse), energy and carbon storage in the implementation of processes;

Development of clean, efficient and safe processes based on the concept of nature-based solutions;

Integration of all Circular Engineering concepts into education programs for process engineers and technicians.

THE FRENCH SOCIETY OF CHEMICAL ENGINEERING

The SFGP brings together all the players in process engineering in France.

The Société Française de Génie des Procédés (SFGP) is an association, created under the French law of 1901. It brings together engineers, technicians, professors and researchers to promote chemical engineering in the chemical, petroleum, pharmaceutical, biotechnology, agri-food, paper and cement industries, as well as 'eco-technological' industries (air, water and waste treatment). The aim of the SFGP is to contribute to the development of process industries in France.

The main missions of the SFGP are to:

- contribute to the national thought process on major issues: the new industrial France, energy and environmental transitions, bio-economy, factory of the future...;
- provide solutions to the technical problems of manufacturers and access to a network of experts
- provide a forum for exchange and brainstorming for all professionals involved in chemical engineering.

The SFGP has a board of 30 members representing industry, engineering schools, universities, EPICs, EPSTs and professional societies.
The themed working groups within the SFGP contribute to scientific and technological progress in the field of chemical engineering by scientific seminars, webinars and colloquia, and by participating in the biennial national congress of the SFGP.
The SFGP is very active in the European Federation of Chemical Engineering (EFCE) and participates in the World Chemical Engineering Council (WCEC). It works along side with other learned societies in France (e.g. Association des Chimistes Ingénieurs et Cadres des Industries Agricoles et Alimentaires, Association Française de Mécanique, Groupe Français des Polymères, Société Française de Chimie, Société Française des Matériaux, Société Française de Thermique) whose fields of activity relate to chemical engineering, as well as with competitiveness clusters such as Axelera.

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