University College London

Department of Chemical Engineering

LIFE CYCLE ASSESSMENT
OF
EMERGING TECHNOLOGIES

FABIO GRIMALDI

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I, Fabio Grimaldi, declare that the Thesis has been composed solely by myself and that the work has not be submitted for any other degree or professional qualification. I confirm that the work is my own and that appropriate credit has been given within this Thesis where reference has been made to the work of others. Where information has been derived from other sources, I confirm that this has been indicated in the Thesis.

ABSTRACT

The environmental impacts of emerging technologies are conventionally identified, regulated, and mitigated only after large-scale deployment. As a result, a considerable number of emerging technologies eventually develop into non-optimized systems, which translate into waste of resources and capitals, and hence reduced competitiveness.

Therefore, it is paramount to assess emerging technologies during the nascent stages of their development and expand the conventional set of metrics of the assessment, thus enabling unbiased decisions on the deployment of the technology and promoting sustainable innovation. The challenge is to ensure that the outcomes of the assessment are not compromised by the uncertainties existing at such early stages of technology development.

Building on these premises, the Thesis lays the foundations for producing high-fidelity and timely projections of environmental impacts and costs of emerging technologies, presenting an overarching framework for prospective assessments, and testing it on four emerging technologies originating from both academic and industrial R&D, at different stages of their process development: 1) production of formate using CO_2 captured from the tail gases of power plants; 2) milli-continuous-flow production of gold nanoparticles for healthcare applications; 3) continuous-flow production of Rufinamide, an anticonvulsant drug; 4) intensified continuous-flow production of zeolite A.

The results of the LCA of emerging technologies demonstrate that is possible to provide live and timely feedback to technology developers and identify intervention points and potential solutions for the optimization of the technology since the early stages. Furthermore, the proposed assessment allows to benchmark the performances of the system under analysis against the standard industrial practice, hence quantifying the benefits that would stem from the adoption of innovative production technologies in place of conventional ones.

On the whole, LCA of emerging technologies offers an opportunity to structure the collaboration between different actors involved in process innovation. The ultimate goal of this approach is to lay the bases for debating and guiding research and development, and to provide a solid platform to discuss with all necessary stakeholders involved in the deployment of the technology, thus promoting sustainable technology innovation.

IMPACT STATEMENT

The area of application of this PhD research interlaces both the academic and industrial sector. The research offers a solid platform – through methodological work and practical examples – that academic and industrial R&D could use to integrate the technology development process. The operationalisation of LCA of emerging technologies in R&D activities enables live and timely feedback to technology developers on environmental and economic performances and hence helps identify intervention points and potential optimization routes for the assessed technology.

Furthermore, this approach entails a synergic collaboration between technology developers and stakeholders from academic and industrial bodies, hence opening opportunities for collaborative partnerships as exemplified in the case studies reported in the Thesis. Funding institutions and investors could use LCA of emerging technologies to evaluate in an anticipatory fashion the potential impacts arising from alternative investment strategies, thus funnelling resources efficiently. The application of the proposed assessment is not confined to a specific technological area: as highlighted in the four case studies of the Thesis, the assessed emerging technologies can stem from the whole spectrum of academic research and industrial sector.

The PhD research presented in the Thesis was funded by the EU MARIE SKŁODOWSKA-CURIE Innovative Training Networks project 'COSMIC'; the project brought together an intersectoral and interdisciplinary network consisting of leading universities and industry participants that set challenging innovation goals to promote sustainable innovation. Such intersectoral context granted a broad exposure to the research, which was cardinal to catalyse the attention of companies and institutions, thus enabling the practical application of this research as shown in the four case studies reported in the Thesis.

Finally, the learnings and the main outcomes of this research were disseminated through conventional communication channels, i.e., scientific papers, international conferences, seminars, discussion panels, and also through less conventional channels, such as blogs, social media (explanatory clips and presentations) in order to reach out to the general public as well as the scientific audience.

ACKNOWLEDGEMENTS

This PhD Thesis is the fruit of the effort and support of several people to whom I am extremely grateful.

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Last but not least, I would like to thank my family. Dad, mom, big bro, you are an inspiration for me. You are humble, sincere, genuinely good, smart, dedicated, strong, resilient and a constant source of serenity.
You don't get to choose who your family is, and I am the luckiest person in the world.

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LIST OF ABBREVIATIONS

A	Acidification
AoP	Areas of Protection
AuNPs	Gold Nanoparticles
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CC	Climate Change
CCF	Cumulative Cash Flow
CF	Continuous Flow
CLCA	Consequential Life Cycle Assessment
COBR	Continuous Oscillatory Baffled Reactor
COSMIC	European project for Continuous Sonication and Microwave Reactors
EcoTOX	Ecotoxicity of Freshwater
ECR-IL	Electrocatalytic Reduction via Ionic Liquids
E fw	Eutrophication of Freshwater
EIA	Environmental Impact Assessment
E mw	Eutrophication of Marine water
EPD	Environmental Product Declaration
ERA	Environmental Risk Assessment
E t	Eutrophication Terrestrial
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gases
GWP	Global Warming Potential
HT c	Human Toxicity (cancer effects)
HT non-c	Human Toxicity (non-cancer effects)
ISO	International Organization for Standardization
ITN	Innovation Training Networks
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Analysis
MFA	Material Flow Analysis

OD	Ozone Depletion Potential
OPEX	Operational Expenditure
PBP	Payback Period
PFD	Process Flow Diagram
PI	Process Intensification
PM	Particulate Matter
POF	Photochemical Ozone Formation
RD m, f, ren	Resource Depletion (minerals, fossil, renewables)
RD water	Resource Depletion (water)
RRI	Responsible Research and Innovation
SDS	Safety Data Sheet
SEA	Strategic Environmental Assessment
SETAC	Society of Environmental Toxicology and Chemistry
TRL	Technology Readiness Level
UNEP	United Nations Environment Programme

THESIS OUTLINE

The Thesis is structured in nine chapters.

Chapter 1 introduces the problem of sustainable development applied to emerging technologies; the rationale behind the fundamental research is identified, and the objectives of the work are stated.

In Chapter 2, the Life Cycle Assessment methodology is described and critically reviewed. The literature review starts from an analysis of the LCA methodology over time, defining the past and current trends of its applications. The analysis then moves on with a critical review of the attempts to the assessment of novel technologies; the research gaps are identified, and the chapter concludes with a summary of the pending challenges and a glimpse at the potential solutions.

Building upon the findings of the literature review, the framework for the assessment of emerging technologies is introduced in Chapter 3. The methodological approach is described and four case studies, on four emerging technologies selected from academic and industrial R&D are presented.

In the central chapters of the Thesis, Chapter 4-7, the proposed framework is put into practice and applied to the selected emerging technologies, each one at a different step of the technology development.

In Chapter 4, the first case study looks into the production of formate using CO_2 captured from the tail gases of powerplants. CO_2 is potentially one of the most abundant feedstocks of chemical precursors that will be available in the next years. To this end, this case study explores the possibility to convert CO_2 into valuable chemicals, like formate, which opens compelling opportunities for simultaneously reducing greenhouse gases emissions and resource depletion in chemicals production. As part of the EPSRC UK project LCF (Low Carbon Fuel), an innovative production system is being developed, based on the electro-catalytic reduction of CO_2 using an ionic (ECR-IL). The environmental impact of this system is quantified at lab scale through the proposed framework, and benchmarked against the conventional production of formate from fossil fuels: the aim is identifying the intervention points in the process development for maximizing the environmental performance of the novel ECR-IL system, and understand under which conditions the novel system can result in performance gains over the conventional production.

The second case study, reported in Chapter 5, focuses on the deployment of a milli-continuous-flow production of gold nanoparticles (AuNPs) for healthcare applications. In this respect, the study gives insights into the environmental impact and costs of the production of

AuNPs for nano-enabled medical applications, by looking at two production technologies: a conventional batch production and an innovative milli-continuous flow production, currently at lab scale. The data originates from an experimental lab setup, developed in UCL's laboratories, as part of the objectives outlined in the EU project COSMIC (European Training Network for Continuous Sonication and Microwave Reactors), and in the EPSRC UK project MAFuMa (Manufacturing Advanced Functional Materials).

In Chapter 6, the third case study explores the effects of scale-up on a solvent-free and continuous-flow mini-pilot plant for the production of Rufinamide, an anticonvulsant drug consumed worldwide for the treatment of epilepsy. The mini-pilot plant originates from industrial R&D, developed at Microinnova GmbH (MIC) in Austria. The environmental and economic performances of the novel technology are discussed and compared with the standard batch synthesis of Rufinamide. Both lab scale and mini-pilot scale setup are investigated in the assessment, and hence consideration on the effect of the scale up are drawn as well as projection on the future deployment of this production technology.

The last study, in Chapter 7, investigates the adoption of an intensified technology for the production of zeolite A, currently being tested industrially at pilot scale. Specifically, the technology under consideration is continuous-flow synthesis using a continuous oscillatory baffled reactor, being developed by Arkema at GRL facilities in Lacq, and currently at pilot-scale. The emerging production system is benchmarked against a batch production system, conventionally adopted at industrial scale.

Afterwards, the outcomes of the literature review, the application of the framework and the results of the case studies, are discussed in Chapter 8 in accordance with the Thesis' objectives set in Chapter 1.

Finally, Chapter 9 sums up the main findings of the Thesis and presents the main recommendations drawn from the work. Future research pathways are outlined.

1 INTRODUCTION

The environmental impacts of emerging technologies are conventionally identified, regulated, and mitigated after large-scale production and dissemination. Early research and development suffer from a lack of integration of environmental research. This is problematic for at least three reasons: (1) virtually all the environmental impacts arising from a technology are triggered by R&D decisions[1]; (2) in the nascent phases of a technology, there is greater flexibility for environmental considerations to guide process development and innovation[2]; (3) uncoupling environmental research from technology development positions assessment and regulation as retrospective and reactive[3].

An alternative approach is to broaden the inputs conventionally considered in the technology development. In place of relying on retrospective approaches, design criteria drawn from environmental evaluations can structure more effective interventions in the early stages of technology development, mitigating, in an anticipatory fashion, the potential environmental impact, and thereby promoting Responsible Research and Innovation (RRI)[4]. However, there is a general reluctance, mainly caused by the lack of comprehensive tools able to practically harmonize environmental considerations into technology R&D.

This Thesis advocates the development and practical application of Life Cycle Assessment (LCA) on emerging technologies as one tool to promote integration of environmental criteria early in the stage-gate innovation model and support the broader goals of sustainable development. In the next section, existing gaps in the current approaches to the assessment of emerging technologies are identified. The Chapter continues with an overview of process intensification in the European context and identifies potential target technologies on which to focus. Following up on these premises, a brief overview of the assessment approach used in the Thesis is reported, and the research objectives are outlined.

1.1 BACKGROUND

1.1.1 LIFE CYCLE ASSESSMENT AND ITS PARADOX

LCA is indeed the most mature and also the only standardized life-cycle methodology – it is a widely accepted tool for supporting decision-making processes by quantifying the environmental impacts associated with goods or services.

Research policy organizations recommend the application of LCA to emerging technologies to reduce the eventuality of unplanned environmental consequences[5,6]. The rationale behind such recommendation is to foster environmental RRI by identifying potential impacts before commercial-scale production and technology diffusion. Conventional approaches to LCA, however, do not support RRI of emerging technologies because they predominantly hinge on data collected from mature processes and hence are retrospective (more details will be presented in Section 2.4). There has been isolated progress in advancing LCA methods toward prospective identification and mitigation of environmental impacts, yet these tools have not been integrated into a comprehensive framework that supports RRI of emerging technologies.

1.1.2 FROM RETROSPECTIVE TO PROSPECTIVE ASSESSMENTS

The majority of LCA studies are retrospective as they are performed after commercial-scale production. Such analyses are useful for informing consumers and regulators about the environmental impacts of a product (e.g. carbon footprints and ecolabeling), yet have limited ability to reorient technology trajectory because temporal delays and large capital investments contribute to technology lock-in. There exists a number of qualitative approaches[7] that can provide useful guidelines early in R&D but lack the quantitative rigor of LCA. To address this deficiency, there have been some attempts to prospective LCA (more on this in Section 2.4.1.1) that employs modelling tools requiring less accurate data sets and that focus analyses on potential environmental impacts arising from R&D decisions. Drawing from diverse fields ranging from future studies to thermodynamics, published advances include incorporation of backcasting[8], foresight tools, and scenario development into LCA and material-flow analysis[9–15], dynamic LCA process modelling[16], and stochastic decision analysis[17–19] (these are reviewed in Section 2.3.3).

The outcomes that these types of approaches provide can be particularly beneficial in those industries where emerging technologies are looked at with reluctance, often because there is not enough clarity on the consequences of their employment in place of the conventional production systems. For instance, Process Intensification (PI) is a strategy that targets established production systems and aims to achieve reduction in capital cost and environmental impact, improved inherent safety and energy efficiency, and improved product quality[20,21]. This has been, during the last two decades, a promising pathway in the development of sustainable and cost-effective chemical process systems, bringing several benefits regarding process efficiency, the use of resources and therefore sustainability[20,22–24]. In the pharma and fine chemical industries, intensified continuous flow (CF) technologies[25–29] are considered clear examples of process intensification, which are able to deliver high-quality products. However, these emerging, intensified technologies are seldom used due to general reluctance of the industries to adopt them, despite their potential. There exists a paucity of assessment of these technologies that contribute to this impasse in innovating established production systems. The consequences of this slow transition are explained in the next section, which gives an overview of process intensification in the European context, and outlines the strategies for responsible research and innovation.

1.1.3 EMERGING TECHNOLOGIES – THE TRANSITION TO INTENSIFIED PRODUCTION SYSTEMS

The European chemical industry faces some very serious challenges if it is to retain its competitive position in the global economy. The new industries setting up in Asia and the Near East are often based on novel process-intensification concepts, leaving Europe desperately searching for a competitive edge[24]. The transition from conventional batch processing to intensified processing is essential to ensure a future for the European fine-chemicals and pharmaceuticals industries. These intensified production technologies can be applied for producing high-value-added chemicals with excellent yield efficiencies – in terms of throughput, waste minimization and product quality – that simply cannot be achieved with traditional batch-type chemical reactors[24].

In 2018 the EU's chemical industry was responsible for approximately €565 billion in sales revenue, making this one of the most important manufacturing sectors, underpinning the overall economic prosperity of the European Union. However, despite the positive aspects associated with the size of this market, the underlying trends do not bode well for the European economy. In reality, the European share of the global chemical market has halved during the period 1996 to 2018 (from ~31% in 1996 to ~17% in 2018) and as a result the number of EU citizens directly employed by this sector has also dramatically fallen (from 1.6 million in 1996 to 1.2 million in 2018)[30]. A key root cause of this decline has been the advent of lower-labour-cost markets in the emerging global economies, and as this labour-cost differential is unlikely to be redressed in the near future, one of the key strategies for halting this decline and subsequently re-establishing European growth is to develop competitive technologies that deliver performance – in terms of resource efficiency and product quality – beyond that of Europe's rivals, in particular those new industries in Asia and the Near East. In order to design and operate these new technologies, new competencies and different skills from scientists and engineers are required. The introduction of revolutionary technologies can indeed only succeed if sufficient professionals trained in these novel technologies are available on the market. Europe's chemical processing industries are generally conservative in nature. This results in their enthusiasm for the "drive to scale" approach, which is based on the economic advantages of scaling up well-understood technologies. The phenomenon is nicely illustrated by the picture in Figure 1.1(left), which shows gold extraction during the Middle Ages[31].

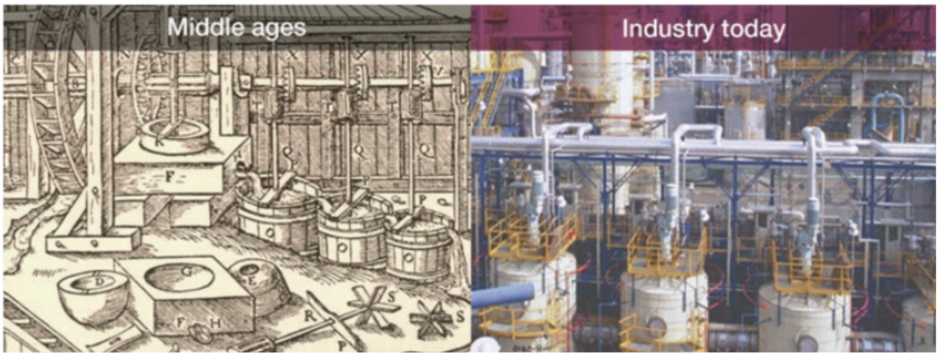


Figure 1.1 - (left) Picture from the gold-extraction industry in the Middle Ages, and (right) batch processing as used in industry today[24].

It is clear that even 500+ years ago both batch processing and continuously stirred tank reactors with overhead impellers were being employed. Now, if we turn to Figure 1.1(right), we see that these same devices – albeit larger and more sophisticated – are still the workhorses of the chemical process industry today. The reluctance to adopt new technologies is primarily because current thinking in the European chemical industry is that any new solution will be more transformation-specific, i.e., it will have little or no potential for grade-change capacity, and will be less safe, compared to the current state of the art. The result of this focus on ever-larger batches is that we have production processes with the following serious drawbacks[24]:

- *Excessive energy consumption:* Large conventional batch geometries exhibit poor surface-to-volume ratios. This drastically limits heat transfer into the reactor as well as mass transfer of undesired by-products from the bulk, and leads to the use of higher wall temperatures and longer residence times, and as a result, excessive amounts of energy are consumed.
- *Variable product quality:* These limitations directly influence the rate and yield of the chemical reactions that occur in any specific reaction mixture, leading to increased by-product formation and/or reductions in selectivity, which also lead to the requirement for additional stages related to the separation and purification of products, resulting in inconsistent product quality.
- *Limited scale-up:* For new-product development, these limitations are exacerbated by the fact that current approaches to the scale-up of new commercial products/ processes typically involve transferring chemistry optimised on a laboratory scale to very large batch reactors that exhibit drastically inferior mass- and heat-transfer characteristics.
- *Poor efficiency, high emissions and limited flexibility*: In addition to the requirement for extra unit operations, the use of such large volumes must be scaled throughout the entire plant assembly, resulting in a large land-usage footprint and increased emissions of waste heat, greenhouse gases and volatile organic compounds (VOCs) from cleaning and grade-change residues. The use of large batch reactors reduces the process flexibility and

> constrains both scheduling and adaptive manufacturing as smaller batch sizes cannot be produced in a repeatable or commercially viable manner. This limited flexibility also destroys the viability of manufacturing products with low volume; a very unfortunate situation as such products are often high margin, or prototype new-product developments.

Intensified continuous flow technology – a clear example of process intensification – offers the potential to address all these issues. This is exactly in line with the findings of the ACS-GCI-Pharmaceutical Roundtable[32], which has specifically identified the demand for novel concepts applied to continuous-reaction systems. Similarly, the European Roadmap for Process Intensification has identified continuous processing as one of the primary objectives for the fine-chemicals and pharmaceuticals industries[33]. For instance, research over the past decade has focused on milli- and micro-structured devices for flow chemistry, which provide several advantages over conventional, and mostly batch, reaction systems[34]. This means a reduction in the size of the equipment and the operational steps, with less energy being consumed, leading to measurable environmental benefits. However, despite their tremendous potential, relatively few relevant applications, out of the numerous ones proposed, have been demonstrated so far. One of the main reasons for this is the existence of crucial knowledge gaps in our scientific and engineering understanding of the impact that these technologies would have on the economics and the sustainability of the targeted production systems as well as the interaction of various process- and equipment- design parameters that determine performance. In order to incentivise the use of a number of emerging technologies that may turn out as disruptive in some manufacturing process and hence attract the interest of industries and investors, it is therefore of crucial importance to fill this gap of knowledge, as outlined in the EU project 'COSMIC'[24] (European Training Network for Continuous Sonication and Microwave Reactors).

To this end, LCA can help the decision-making process by quantifying the environmental impacts associated with goods or services. When used in parallel with a comprehensive analysis of capital and operational expenditures, the result is an overarching assessment of the environmental performance and economic robustness of the target production system. In the case of emerging technologies, these type of assessment would render more complete the set of knowledge and projections of the future performance of these new technologies, thus facilitating the decision making process when investing in new technologies; these type of assessments could potentially play a major role in the fate of many of those intensified production technologies that are today available in several sectors of the chemical industry, but that don't have enough momentum to reach commercial scale. However, many challenges stand in the way when forecasting the environmental performances and cost of a virgin system that has yet to reach its final form.

1.2 TOWARDS THE ASSESSMENT OF EMERGING TECHNOLOGIES – THE PROPOSED APPROACH

There is a window of opportunity to shape up LCA into a tool to guide RRI by building on prospective modelling advances and exploring multiple scenarios, taking into account different process configurations, effect of production scale and strategies for the deployment of the technology. The aim is to create a tool that assimilates environmental considerations into the development process, and hence anticipates foreseeable negative consequences, identifies opportunities for improving the environmental performance of emerging technologies, and communicates findings in time to reorient research. Not all processes reach commercial scale, and this translates into loss of human and capital resources. Furthermore, their development can be costly, time consuming and involve long procedures for their implementation[35]. Therefore, emerging technologies need to be filtered from early stages to prevent waste of resources which lead to high costs and reduce competitiveness.

To this end, the early screening and filtration of emerging technologies requires a high level of knowledge of the process. Such knowledge, however, is usually only obtained at later stages of their development. This calls for the need of a type of assessment that is able to provide a faithful rendering of the environmental impact[36] and costs throughout the process development of an emerging technology[37]. A visual representation of this is shown in Figure 1.2.

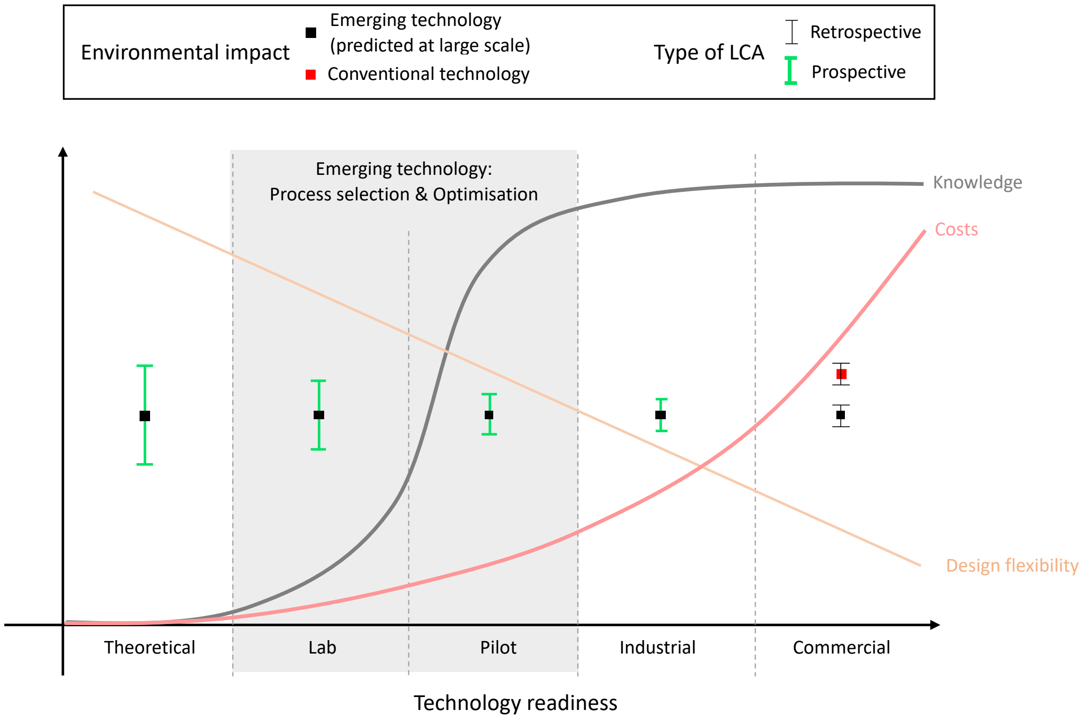


Figure 1.2 - Output of different approaches to assessment along the process development of an emerging technology.

This type of assessment should hence quantify the uncertainty and variability of the results depending on the scale of the system[38], and identify the 'hotspots' of the system on which to focus the subsequent phases of the development.

Furthermore, the outcomes of the assessment serve as input to the technology development for optimizing it towards low environmental impacts and high economic performance. Finally, the performance of the system under analysis can be benchmarked against the standard industrial practice, thus quantifying the benefits stemming from the adoption of such innovative production technologies in place of conventional ones.

Building upon these premises, this Thesis present an anticipatory LCA approach in order to intervene early in the process development of emerging technology and optimize their environmental performances. The overview of the concept is reported in Figure 1.3 that shows schematically the proposed approach and the expected outcomes of the latter.

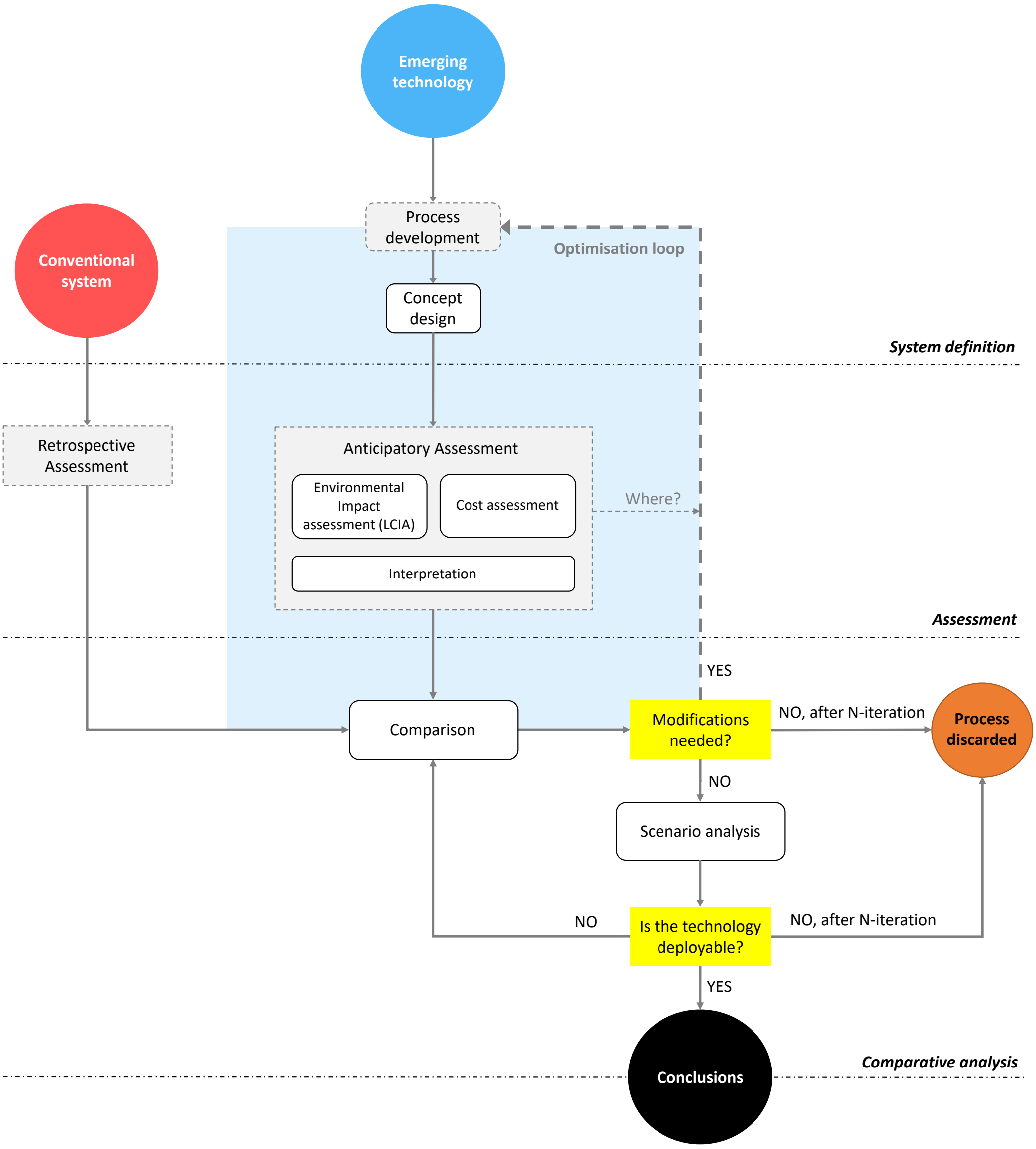


Figure 1.3 - Schematic representation of the proposed approach.

In the schematic, the intervention points for retrospective and anticipatory LCA are identified, along with the resulting decision-making process that such approach enables. Retrospective LCA – usually performed after commercial production and diffusion to filter out unacceptable technologies and used as a tool to maintain compliance – is used in this Thesis to assess environmental impacts and costs of production systems conventionally adopted in industry at commercial scale. This provide the reference line against which environmental performances and economics of the selected emerging technology, obtained through anticipatory LCA, are benchmarked.

Following up on the definition of the framework, this Thesis applies this overarching framework on four emerging technologies selected from academic research and industrial R&D activity. The emerging technologies subjected to evaluation have a low level of maturity, namely low Technology Readiness Level (TRL); these are in fact assessed either at lab or pilot scale, equivalent to TLR 3-5, in the central-bottom end of the thermometer of technology readiness (as shown in Figure 1.4). As pointed out previously, this is paramount to enable timely interventions in the technology development, and still have the ability to reorient the technology trajectory.

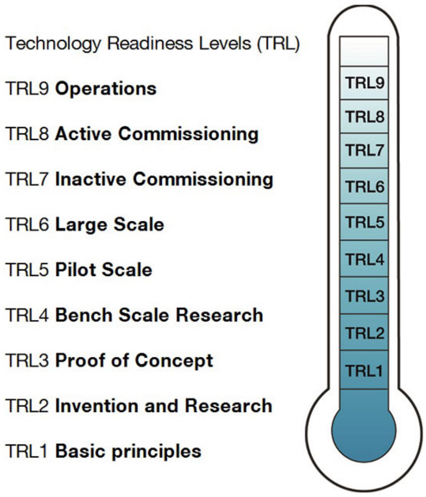


Figure 1.4 - Technology Readiness Level (TRL) scale (source: https://www.gov.uk).

The four case studies analyze technologies at different stages of the process development – i.e. different production scales. Specifically, the first two case studies look into two novel technologies at lab and bench scale originating from academic research: the production of formate using CO_2 captured from the tail gases of power plants, and the milli-continuous-flow production of gold nanoparticles for healthcare applications. Afterwards, the focus of the Thesis moves onto industrial R&D where two technologies are analysed at a more mature stage of process development. The third case study explores the effects of the scale-up on a mini-pilot plant for the continuous-flow production of Rufinamide, an anticonvulsant drug.

Finally, the fourth study investigates the adoption of an intensified technology for the production of zeolite A, currently being tested industrially at full pilot scale.

In these studies, the innovative production system is assessed at the early stages of its development; the latter is taken from the lab/pilot-scale setup, scaled up/out conceptually to full scale, and subsequently subjected to evaluation. The results of the environmental impact and cost assessment are then compared with a reference technology, namely the process conventionally adopted in the industry for commercial production. The environmental performances and production costs of these production systems are discussed from several perspectives.

The objectives of the Thesis are presented in the next section.

1.3 RESEARCH OBJECTIVES

This Thesis investigates the possibility to shift the scope of the LCA from retrospective evaluations of already established technologies to prospective evaluations of emerging technologies, that are yet to be deployed. The overall goal is to define a framework for the evaluation of novel technologies at early stages of the process development, and consequently put the latter framework into practice on selected production technologies.

In order to achieve this, a thorough literature review is conducted. The aim of this first step (which will be referred to as '**OBJECTIVE I'**) is to:

- Review past and current trends in the application of the LCA methodology in order to understand the evolution's trajectory of the methodology.
- Identify the main challenges and research gaps in the definition of a prospective LCA methodology and its practical application.
- Critically analyze the existing research gaps and derive potential solutions.

Building upon the main findings of the literature review, the next objective ('**OBJECTIVE II'**) is to present a framework for the assessments of emerging technologies, defining an approach to overcome the major challenges identified through the literature analysis and embedding the latter approach into the proposed framework.

After having defined the methodological framework for the assessment of emerging technologies, the focus of the Thesis shifts onto the practical application of the framework on case studies selected from academic and industrial R&D. The four case studies are emerging technologies that are currently being developed with the aim of integrating/replacing conventional production systems; the latter aim is contingent on their environmental and economic performances that these emerging technologies will have once deployed at large scale. Hence, the application of LCA on emerging technologies is tested at different stages of the process development, i.e. at different scales. Each case study, in fact, addresses different challenges because of the different level of technology development (TRL) that spans from the proof-of-concept stage at lab scale to full pilot scale. Specifically, the electrochemical conversion of captured CO_2 to formate – case study I – is in the proof of concept phase (TRL 3), the continuous flow production of gold nanoparticles for medical applications – case study II – is at bench scale (TRL 4), the continuous flow production of Rufinamide – case study III – is currently at mini-pilot scale (TRL 4.5), and finally the continuous flow production of zeolite A – case study IV – at full pilot scale (TRL 5). To this end, the **'OBJECTIVE III'** can be divided in two subsets: *macro-targets*, which consider a broad perspective and embrace all the case studies, and *micro-targets* that are case-specific.

The subset of *macro-targets* consists in:

- Testing the feasibility of applying the framework at different scales and capturing the possible limitations imposed to the analysis under different TRLs.
- Investigating how the projection of the environmental impacts varies with different scales.

The subset of *micro-targets* consists in:

- Calculating case-specific environmental impacts for each of the selected technologies; the case studies are subjected to different analyses, i.e. hotspot, normalization, scenario and uncertainty analysis, each one presenting a different angle of the environmental performances of the systems analyzed.
- Understanding how the results of the environmental impact assessment can be used for providing guidance in the next steps of the process development for each one of the case studies under analysis. In other words, the aim is to identify the potential intervention points in the process development to optimize their performances.

Along with the assessment of the environmental impact of the selected emerging technologies, the Thesis explores an economic perspective. In parallel with the environmental impact assessment, a cost assessment is undertaken: in this case, the objective (**'OBJECTIVE IV')** is to provide an additional criterion of selection and evaluation of emerging technologies to the analysis by integrating the results of the environmental impact assessment with considerations from the economic sphere.

Furthermore, the performances of these novel technologies are benchmarked through a comparative analysis against the state-of-the-art technologies, conventionally adopted at industrial scale. As stated in section 1.1.3, one of the main focal points of the EU project 'COSMIC', which funded the research reported in this Thesis, is to discuss the feasibility of a transition from batch to intensified continuous flow processing. To this end, the **'OBJECTIVE V'** consists in outlining conclusions on the environmental and economic performances of continuous flow productions compared to traditional batch synthesis, and therefore discuss the environmental and economic implications of a general transition from batch to intensified continuous flow processing.

Finally, the last goal is to summarize the types of outcome obtained through the LCA on emerging technologies and identify the audience and the expected impact of this approach to the assessment, alongside with possible future works as follow ups to this research.

2 LITERATURE REVIEW

2.1 CHAPTER SUMMARY

In this chapter, the Life Cycle Assessment methodology is critically reviewed. The review starts with a detailed description of the methodological steps involved in the assessment. Successively, the focus shifts on a temporal analysis of the LCA methodology, investigating how the latter has changed over time; past and current trends of its applications are identified. Narrowing down the scope on the most recent applications of the LCA, the chapter follows on with a literature review of the attempts to the assessment of emerging technologies. Practical applications and methodological works are examined thoroughly in this section, in order to build awareness of failures and successes, filter out unproductive information and extract knowledge to be carried on and further developed. The research gaps are identified; finally, the chapter concludes with a summary of the pending challenges and outlines potential solutions to embed in the Thesis' framework for the assessment of emerging technologies.

2.2 LIFE CYCLE ASSESSMENT (LCA): THE CONVENTIONAL METHODOLOGY

2.2.1 THE DEVELOPMENT OF THE LCA CONCEPT

As concerns about the environment have become primary points of discussion and drivers for policy makers, public administrator, businesses and individuals, the approach to integrating environmental considerations into challenging decisions about our society have been increasingly valued in recent years[39]. For this purpose many tools and indicators for assessing and benchmarking environmental impacts have been developed[40,41]; examples include, Life Cycle Assessment (LCA), Strategic Environmental Assessment (SEA), Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA), Cost-Benefit Analysis (CBA), Material Flow Analysis (MFA) and Ecological Footprint. Amongst those, LCA and the life cycle perspective are gaining increased interest as demonstrated by their inclusion into EU legislation, for example through the Integrated Product Policy[42,43]. The LCA tool can act as a supportive tool for decision makers and decision-making processes by evaluating the environmental burdens associated with a product or technology[44–46]. In addition to the above, many other applications may be identified, including market communication and product development[44]. Notably, the term product includes both goods and services, while technology encompasses a range of different processes delivering the same product or service[47]. As opposed to other environmental tools, LCA is a comprehensive assessment that embraces all types of impacts commonly represented under the three areas of protection: Human Health, Environment and Natural Resources. The unique feature of LCA, its main difference and advantage over other environmental tools, is the focus on "system thinking", on products and technologies with a life cycle perspective. The comprehensive scope of LCA is useful to avoid problem-shifting, for example from one phase of the life-cycle to another, from one region to another, and even from one environmental problem to another[48].

Besides universities, several national and international organisations are involved at present in the continuous development of LCA at various levels: these include SETAC, the ISO and the United Nations Environment Programme (UNEP). Research undertaken in academia and organisations also lead to the development of several LCA methods, each trying to adapt the standard LCA methodology to specific applications.

2.2.2 THE FRAMEWORK

The ISO international standards establish the LCA as a rigorous approach for the analysis of the environmental burdens of a product or a service. The LCA methodology consists of four phases, as reported in Figure 2.1:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

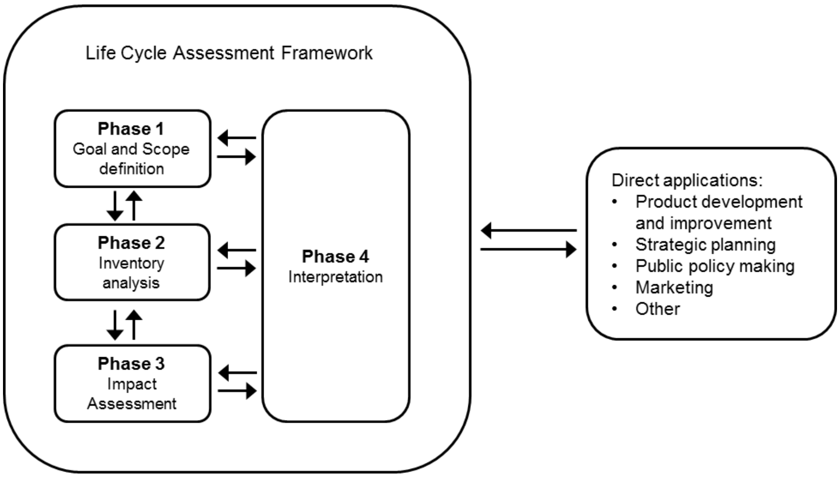


Figure 2.1 - Phases of Life cycle Assessment[49].

It must be noted that an LCA study is an iterative process because earlier phases may be revisited in light of the results of later phases. Changes in the material input to a manufacturing process or changes in the process itself may trigger the need to update the inventory component; whilst new information about the impact of substances on the environment will require the Impact Assessment to be updated. Thus, the continuous interaction between the components of an LCA is essential for a successful study. It is, however, important to recognise that phases such as Impact Assessment are continuously developing, and further work is required in several areas. The four phases of LCA are explained in the following Sections.

2.2.3 GOAL AND SCOPE DEFINITION

At the outset, it is essential that the purpose of the study be defined unambiguously; this includes the reason for carrying out the study, its intended application and the intended audience. If decision support is the primary reason, what decision the study is intended to inform also needs to be included.

The scope of the study has to include a clear statement on the specifications of the functions of the product, quantified by the functional unit, and on the processes and operations which are to be considered, expressed in terms of the system boundary. These concepts are explained in the following sub-sections.

Finally, in the goal and scope definition also the principles for allocation, data quality requirements and choice of impact categories and method for impact assessment have to be specified.

2.2.3.1 Functional unit

The functional unit quantifies the function of the product under study. Its primary purpose is to provide a reference to which input and output data are normalized; it is thus essential that the functional unit is clearly defined and measurable. As LCA studies are commonly performed to compare alternative ways of delivering some function, the functional unit also serves as a basis for the comparison. It must be noted that the results of an LCA study are strongly related to the choice of the functional unit, and thus functional units and results must not be separated.

2.2.3.2 System boundaries

The system boundaries separate the technical system, which includes all the activities part or affected by the life cycle of the product, from the surrounding environment (Figure 2.2). Material or energy flows between processes are named technical flows, whereas flows between processes and the surrounding environment, that is those flows that cross the system boundaries, are named elementary flows. An elementary flow is otherwise defined as a material or energy entering in the system which has been drawn directly from the environment without previous human transformation; or a material or energy leaving the system, or discarded into the environment without subsequent human alteration. Ideally, the technical system should be modelled in a way that all inputs and outputs are elementary flows. However, this is not practical due to time and other constraints, and often not feasible due to lack of data; therefore, decisions should be taken as to which processes are to be included. These considerations have to be included in the goal and scope definition.

Many authors[50–52] suggest dividing the technical system into a foreground and a background, as shown in Figure 2.2. These concepts were developed in 1999 in the SETAC working group on enhancement of inventory methodology[53]: the foreground system comprises "the set of processes whose selection or mode of operation is affected directly by decisions based on the study"; the background system comprises "all other processes which interact with the foreground, usually by supplying or receiving material or energy". It was also reported that a sufficient but not necessary condition for a process to be in the background is that the exchange with the foreground takes place through a homogeneous market [51]. The distinction between foreground and background does not imply any distinction due to the importance of the burden related to those systems - the environmental loads of anyone of the two can be the largest. The division of the technical system between foreground and background can also guide the choice of the type of data to be used: Clift et al.[51] advise to use preferably primary data for the foreground and secondary data for the background.

As noted previously, a distinguishing feature of the attributional and consequential approaches lie in how system boundaries are drawn: typically, CLCA studies use enlarged system boundaries to include the affected processes by the decisions under investigation. Sandén and Karlström identified three typologies of consequences – that is three types of cause-effect mechanisms - of use in consequential studies[54]:

1. First order effects represent the linear systemic response to marginal changes in the product system. For instance, an incremental change in production may result in the avoided production of a competitor's product, for which the system is credited.
2. Second order effects include indirect consequences governed by negative feedback. These take into account the economic flows related to the physical flows, and are propagated by price mechanism controlling the supply of different goods and services. For instance, a marginal change can affect the price of the product itself and of competitors' products, which may lead to a shift to a new equilibrium between demand and supply: the system is credited according to the new equilibrium. Notably, these effects are included by using partial or general equilibrium models (e.g. Dandres et al., 2011[55]; Ekvall and Andrae, 2006[56]; Kløverpris et al., 2008[57] and 2010[58]; Lesage et al., 2007[59–61]).
3. Third order effects include indirect consequences governed by positive feedback. These consider the effects of the cumulative build-up of stocks, structures and knowledge in producers, users and institutions, quantified in terms of cost reductions by using an experience curve; and are especially relevant for emerging technologies. Third order

effects are used to allocate future potential avoided emissions to a current investment into an emerging technology. For instance, the economies of scale may lead to increased performance to cost ratio when more units are produced or to an adaption of regulations and the educations system: in this way early investment in radically new technology may set in motion a self-re-enforcing process.

First and second order effects are often incorporated in consequential modelling; however, this is not the case for third order effects, perhaps due to difficulties in their integration in the LCA framework. Notably, second order effects are typical of neo-classical economics, whilst third order effects are drawn by theories of technical change[62].

The types of consequences to be included in an LCA study depend on its goal, on the technical readiness levels (i.e. mature vs emerging) and on the time frame (i.e. short vs long term effects). For each consequence, the specific processes (namely "marginal technology) to be included in the system boundaries need to be identified. For this purpose, Weidema et al. developed a five-step procedure to support the identification of the most relevant marginal technologies for each specific case[63]. However, Mathiesen et al.[64] argued that, because LCA results are very sensitive to the choice of the marginal technology, a range of marginal technologies – rather than a single one - should be used. From an historical analysis of the Danish energy sector they demonstrated that when applying the theoretical recommendations of consequential LCA to the identification of the marginal technology, the actual marginal technology is never identical with the one predicted by CLCA.

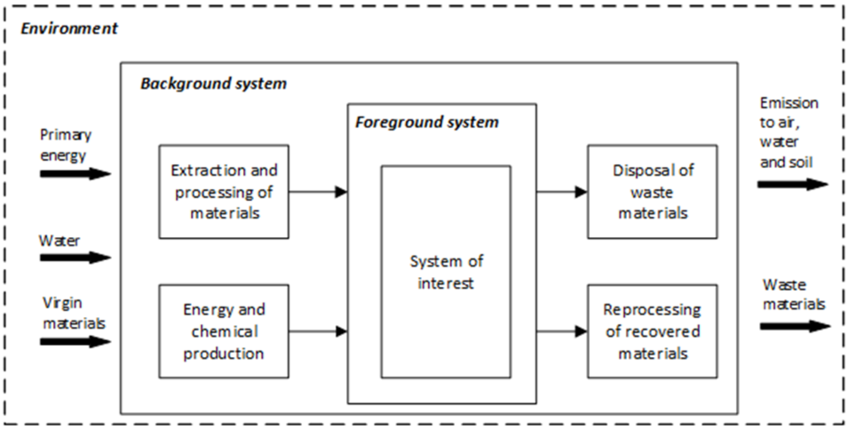


Figure 2.2 - Boundaries of a generic system.

2.2.4 LIFE CYCLE INVENTORY

As stated by the ISO 14040 "inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system". This implies that by means of the inventory analysis, it is possible to understand in advance whether the resources utilization and releases to the environmental matrices will be relevant, or not.

At the basis of the inventory analysis there is the gathering of data concerning the foreground system to be used as input for the modelling part. The final inventory should be referring to the reference flow that fulfils the functional unit, previously defined.

Usually, Life Cycle Inventory (LCI) is the phase with the high demand of time and effort because of the difficulties of collecting high quality data for all the processes. Of course, for the final achievement of the goal of the study not all the data are required, and sometimes it may be possible to apply some cut-offs, if these do not influence the results from the impact assessment (LCIA) phase.

Frequently, LCA practitioners found themselves dealing with issues concerning how to handle the multi-functionality of processes, which happens when a process provides more than one service or has more than one output. To solve this problem the ISO provides a hierarchy to be followed. The last step in the LCI analysis is the creation of models and the calculation of LCI results, which will be used in the LCIA phase in order to quantify the environmental impacts.

2.2.4.1 Data collection

A fundamental action, necessary before starting the data collection, is to identify all the processes involved in the system under investigation. This can be done starting with discriminating the unit process having as output the reference flow -which is the flow satisfying the function quantified by the FU[65], and trying to determine the upstream and downstream processes of the foreground system.

The data used in the model should be representative as much as possible of the system under study, and its possible variations, thus it is recommended that the data should represent the full production cycle, to consider not just the production itself, but also the wastes originated during the operational cycle, plus all the activities of heating, calibration, cleaning, and maintenance over a determined period of time. Usually the data are collected over 1 year of production cycle, and then scaled to the quantity chosen as reference flow.[66]

Data should be collected for each unit process included in the defined system boundaries. These data are classified by the ISO as:

- "Energy inputs, raw materials, ancillary inputs, other physical inputs,
- Products, co-products and waste,
- Emissions to air, discharges to water and soil, and
- Other environmental aspects."

High quality primary data, from direct measurements at specific site, or derived from measurements in specific site, should always be preferred, over medium and low primary data; even though they are very time and resource consuming to get.

Sometimes, it might happen that the companies themselves have scarce knowledge concerning the input and output flows of some production units. In these cases, the material and energy streams can be estimated by using data referring to the same processes, but taking place in other sites, or using data from technical reports, scientific literature and LCI databases (secondary data sources).

Secondary data, such as average industrial data, data from reports or scientific literature, can be used to describe the background system in attributional LCA; whilst in consequential LCA the average-market data, due to their uncertainty on which process is superseded, are not suitable, and marginal data are required. When modelling and gathering data for a consequential system it is always necessary to understand:

1. whether or not the increase and decrease of the demand of a product will have effects on the supply of that product;
2. the technology affected by the change, and
3. if any product will be substituted (and by which) or not.

To conclude, many of the databases are based on average data, which represent the average production and supply for goods, and can be employed in attributional LCA[67]. Unit process data, on the other hand, represent specific technologies, and thus gives the possibility to the practitioner to tailor the inventory by choosing the technology needed for modelling a consequential LCA system. Moreover, since unit process data are not aggregated as the average data, eventually they can be tailored to a specific geographic and temporal situation, or to other modelling principle required for the study.[67]

Usually, primary data are collected by the practitioner using questionnaire built *ad-hoc* to be filled in by the client. There are cases in which the companies are not willing to communicate to the practitioner internal data, because of their confidentiality. To overcome this problem, it is good to sign a non-disclosure agreement and not report any relevant data in the main public documentation.

A time-consuming task for LCA practitioners is the preparation of questionnaires; this because they have to be easily understandable by companies in order to be filled in correctly. The questionnaire should ask for the required data flows, the units and the quality of data. In preparing the questionnaire, the practitioners should remember to keep the questionnaire flexible to changes.

2.2.4.2 Cut-offs

Sometimes in LCA it is possible to apply “cut-offs” of process unit, not reference flows or life cycle stages, if these are not quantitatively relevant. The “cut-offs” imply to not account for one or more elements, if these do not carry more than 5% of the total environmental impacts[68]. Of course, this is a paradox, since for applying a cut-off you should have a rough estimation of the total impact. This issue can be overcome defining a completeness percentage that depends on the detail of interest of the system. In case of comparative LCA, the cut-off criteria must be defined on the basis of the precision, accuracy and completeness required to highlight the differences among the systems.

2.2.4.3 Multi-functional processes

Either during the definition of the system boundaries, or the inventory compilation, it is possible to find out that one or more processes have more than one output becoming inputs for different supply chains. In these cases, it could be difficult to establish the environmental impacts related only to the output of interest, and more difficult to establish a common procedure to be followed by the practitioners.

To solve this problem, the ISO 14044 defines a hierarchy of possible approaches to be applied to handle the multi-functionality.

1. *Subdivision* in sub-processes, as the ISO states, should always be the first choice to solve multi-functionality issue. Subdivision is basically a zoom in on the process to understand whether the multi-functions are artificial, or not. Generally, multi-functions depend on the level of detail at which the system is studied; it may be possible that one process can be divided in 2 or more sub-processes, and thus it is possible to separate the 2 or more outputs previously identified as one flow coming from the same process unit. Applying the subdivision means cutting-off all the processes providing secondary functions. Unfortunately, in almost all the biological and in many chemical processes, the multi-functionality cannot be solved by subdivision, but it might be necessary to apply a crediting/system expansion approach, or at last an allocation.[66]
2. *System expansion and crediting* are the second approaches suggested by the ISO. These two ways of dealing with the multi-functionality are conceptually two distinct methods, even though they are mathematically the same. System expansion is applied in comparative studies, when one system provides more than one functions than the other. A process providing the secondary function is added to the system boundaries of the mono-functional system, in this way the multifunction system can be compared with the mono-functional one.

   The crediting approach, instead, is usually employed in non-comparative attributional LCA, and consists in subtracting from a multi-functional system the impacts related to a mono-functional process delivering the secondary function.[69]
3. Finally, ISO 14044 suggests using *allocation* in case the first two approaches are not feasible. Allocation refers to the action of partitioning all the inputs and outputs among the products (functions). The ISO recommends employing the allocation on the basis of

the physical relationships between the flows and the products, and that when this is not possible, other kind of relationships should be considered, such as economic value of the co-products. Of course, special attention should be paid in order to maintain a material balance throughout the entire inventory. Moreover, for consistency reasons allocation should be uniformly employed to similar inputs and outputs of the system.

Due to the difference of objectives, the modelling of a consequential inventory differs from modelling an attributional LCA. In case of multi-outputs processes, when the subdivision is not possible, the system expansion approach is always applied[70].

In case of reuse and recycling, a system can be defined as multifunctional, and thus it may require understanding how to solve it. The reuse and/or recycling can happen in two ways: closed-loop that means the materials do not leave the product system where they have been generated, the materials are recycled without any changes to their properties; and open-loop happening when a material from a system undergoes recycling and after that enters a new system. Often this happens because after the recycling the material presents changed properties, making it not suitable for being used in the same production system.[71]

Generally, in a closed-loop scenario, the multi-functionality of the system is not a problem, because the recycled materials displace the primary/virgin ones. Instead, in an open-loop scenario in which the materials change their properties and are utilised as input for another system, it is necessary to deal with the multi-functional issue following the ISO 14044 hierarchy:

1. physical allocation;
2. economic allocation, and
3. allocation based on the number of subsequent uses of the recycled material.

2.2.4.4 LCI results and analysis

Once all relevant data have been gathered and the model has been built with all the flows referring and scaled to the functional unit, it is possible to calculate the results of the inventory, represented by all the elementary flows. In other words, in this phase all the flows are converted into elementary flows (material and energy entering/leaving the system without any human transformation), whicb are the basis for the calculation of the environmental impacts in the following phase, the Life Cycle Impact Assessment (LCIA).

Nowadays, thanks to the available LCA software, such as SimaPro, GaBi, OpenLCA, Umberto, and the LCA databases, the LCA practitioners can calculate the LCI results very quickly.

2.2.5 LIFE CYCLE IMPACT ASSESSMENT

2.2.5.1 Introduction

The third phase of an LCA study, Life Cycle Impact Assessment (LCIA) phase translates the elementary flows described in the life cycle inventory into environmental impact scores. It assesses the magnitude of contribution of each flow (i.e. emissions or resource use of a product system) to an impact on the environment. The LCIA phase also provides information for the life cycle interpretation phase. The objective is to make the results more environmentally relevant, comprehensible and easier to communicate. This is achieved by using impact categories and category indicators associated with the result of the inventory analysis. The number of inventory results parameters can range from a few dozens to hundreds, making the output of the study difficult to understand. Through the LCIA, the number of parameters can be reduced, by grouping the environmental loads of the LCI into environmental impact categories.

An environmental impact can be defined as a set of environmental changes due to causes originating in human activities. These impacts are calculated using a wide range of qualitative and quantitative tools that transform the output of the LCI into a readable *environmental consequence*. For instance, 1 kg of methane emitted into air does not have the same impact on climate change as 1 kg of CO_2, even though their emitted quantities are the same since methane is a stronger greenhouse gas (GHG). LCIA characterisation methods essentially model the environmental mechanism that underlies each of the impact categories as a cause-effect chain starting from the environmental intervention (emission or physical interaction) all the way to its impact. The results of a LCIA should not be considered as actual environmental effects, though. They just represent a potential impact.

The ISO 14040/14044 standards distinguish mandatory and optional steps for the LCIA phase (Figure 2.3).

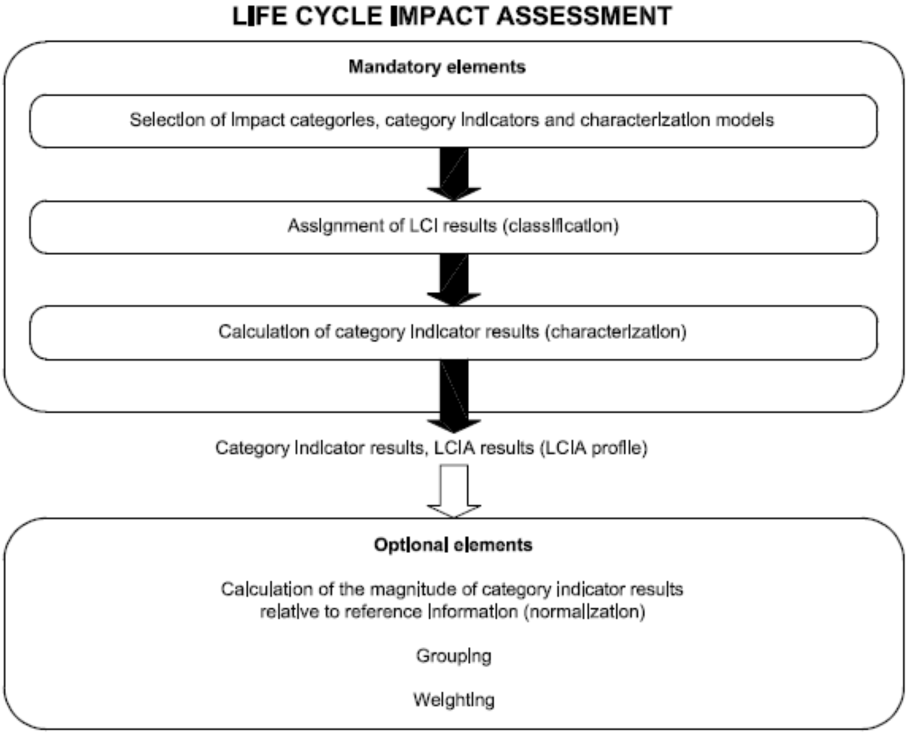


Figure 2.3 - Elements of the LCIA (source ISO 14040, 2006)[65].

Mandatory steps:

- Selection of impact categories, category indicators and characterisation models

  In this step the impact to assess is identified

- Classification (assignment of LCI results to impact categories according to their potential effects)

  Each contribution of the LCI output is linked to an impact

- Characterisation (calculation of category indicator results with quantification of the contributions from LCI flows to each impact categories)

  The magnitude of the LCI result contribution is calculated

Optional steps:

- Normalisation

  Calculated impacts are compared to a reference system

- Weighting

  Each impact category is assigned a weight on the basis of its priority

- Grouping

  Different impact indicator results are aggregated into groups

Table 2.1 - Terminology and relative explanatory examples.

Term	Example
Impact category	Climate change
LCI results	Amount of a greenhouse gas per functional unit
Characterization model	Baseline model of 100 years of the Intergovernmental Panel on Climate Change`
Category Indicator	Infrared radiative force (W/m^2)
Characterization factor	Global warming potential (GWP_{100}) for each greenhouse gas (kg CO_2-equivalent/kg gas)
Category indicator results	Kilograms of CO_2-equivalents per functional unit
Category endpoints	Coral reefs, forests, crops
Environmental relevance	Infrared radiative forcing is a proxy for potential effects on the climate, depending on the integrated atmospheric heat adsorption caused by emissions and the distribution over time of the heat absorption

2.2.5.2 Selection of impact categories, category indicators and characterisation models

The reason behind selecting impact categories, category indicators and characterisation models is to find the most useful and functional ones for the goal of the study. The selection of impact categories must be coherent with the goal of the study in order to correctly direct the collection of information on the relevant elementary flow in the LCI. This is done in the scope definition phase before the collection of inventory data to ensure that the latter is targeted towards what is to be assessed in the end. The determination of the criterion that defines what is essential for the study is often not straightforward.

Some criteria are given by ISO 14044, as requirements and recommendations. ISO 14044 states that the choice of impact categories needs to assure that they:

- Are not redundant and do not lead to double counting.
- Do not disguise significant impacts.
- Are complete.
- Allow traceability.

In addition, this list is accompanied by obligatory criteria. On the basis of these criteria, the selection of impact categories, category indicators and characterisation models need to be:

- Consistent and justified with the goal and scope of the study.
- Comprehensive about environmental issues related to the considered product system (meaning that all environmental issues affected by a given product system must be included in order to highlight any problem-shifting from one impact category to another).
- Well documented with all information and sources being referenced (usually achieved providing name and version number of the LCIA method used together with references used to build the method.

ISO 14044 recommendations for the selection of impact categories, category indicators and characterisation models also comprise:

- The impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body.
- The impact categories should represent the aggregated impacts of inputs and outputs of the product system on the category endpoint(s) through the category indicators
- Value-choices and assumptions made during the selection of impact categories, category indicators and characterization models should be minimized.
- The impact categories, category indicators and characterization models should avoid double counting unless required by the goal and scope definition, for example when the study includes both human health and carcinogenicity.
- The characterization model for each category indicator should be scientifically and technically valid, and based upon distinct identifiable environmental mechanisms and reproducible empirical observation.
- The extent to which the characterization model and the characterization factors are scientifically and technically valid should be identified.
- The category indicators should be environmentally relevant.

In a usual LCA practice, a group of category indicators, based on specific characterisation models is integrated into sets or methods, called life cycle impact assessment methods or LCIA methods[72,73]. These sets (i.e. ReCiPe, CML, TRACI, EDIP, LIME, IMPACT 2002+, etc.) are generally implemented in LCA software. As an increasing number of LCIA sets and indicators are available, the choice of the best suitable one for a practitioner’s study should require a deep understanding of the main characteristics of these methods. It is also needed to take into account the evolution of these methods as they are subject to continuous updates and merging.

2.2.5.3 Classification

In this step the LCI results are sorted and assigned to the impact categories to which they contribute. This requires some knowledge of what the implications on the environment of the impact pollutants and resource use are. For example, the practitioner needs to know that an emission of NO_x can be assigned to acidification and eutrophication category and even to photochemical oxidation potential, given the nature of this pollutant. This can have in fact multiple impacts in two modes:

- Parallel: a certain substance has a number of impacts, occurring simultaneously (i.e. NO_x impacting on acidification and eutrophication category)

- Series: a certain substance has an impact that causes a chain of effect involving other impact categories (i.e. NO_x can take part in chemical reactions leading to photo-oxidant formation)

This step is usually performed via pre-compiled LCA software, based on classification tables, as it requires a deep knowledge and understanding of the nature of the considered substance and the pathways and transformations it goes through once emitted.

2.2.5.4 Characterisation

Characterisation is a quantitative step in which all elementary flows described in LCI are assigned a magnitude of how much they contribute to a specific impact category.

$$Impact_i = \sum_j (CF_j * E_j)$$

where *i* is the considered impact category and *j* is a given emission or resource extraction. The impact is then the sum over all interventions *j*, of the elementary flows, classified within a specific impact category *i*, multiplied by their respective characterisation factor (*CF*). The unit is given by the characterisation factor and is equal for all elementary flows classified under the same impact category.

A characterisation factor is the impact contribution per unit of elementary flow, to a specific impact category. It is calculated using quantitative models based on the cause-effect chain of events leading to the impact on the environment (adverse effects). These models are usually composed of four main steps, after the pollutant has been emitted or the extraction or use has occurred:

- Fate

    This step describes the transport, partitioning and transformation of the considered substance in the environment. It is based on chemical and physical properties of the substance and on the characteristic of the media in which the substance is located into. The output is usually given in mass of the substance in a given region of the environment per emission rate.

- Exposure

    It describes the exposure of a given target (i.e. humans, animals, plants, ecosystems) to a given substance. The process can involve a number of exposure routes (i.e. for human exposure, inhalation, ingestion dermal contact etc.). The unit used in this step is usually in-taken mass rate of the considered substance per unit of mass in a given region of the environment.

- Effects

  This step is focused on assessing the number of adverse effects caused by the exposure to a given substance (i.e. increase of diseases cases, death, etc.). It is generally expressed in number of adverse effects, per unit of intake in the considered specie or ecosystem.
- Damage

  It weights the adverse effects observed in the previous step by quantifying the number of potential irreversible consequences or death, for human health or potentially disappearing species, for ecosystems. The characteristic unit used in this step is usually the chosen end effect per number of adverse cases observed.

The characterisation can be performed at mid-point or end-point level.

Characterisation at midpoint level results in a series of impact indicators that gather the elementary flows from life cycle inventory according to their ability to contribute to the same environmental effect. This characterisation leads to the definition of an impact profile of the product system that can be reported as the result of the LCA study or it can be used as a preparation basis for assessing the impact on an endpoint level.

An additional modelling is required to expand a midpoint indicator to an endpoint indicator. This step of modelling is usually called damage or severity modelling. The meaning of an endpoint indicator is translating the output coming from midpoint indicators to different topics or Areas of Protection (AoP) that are usually representative of human health, natural environment and natural resources. In other words, the endpoint indicators describe the very end of the cause-effect chain of the environmental mechanism activated by the elementary flows assessed in the LCI, while midpoints indicators lie in between (see Figure 2.4).

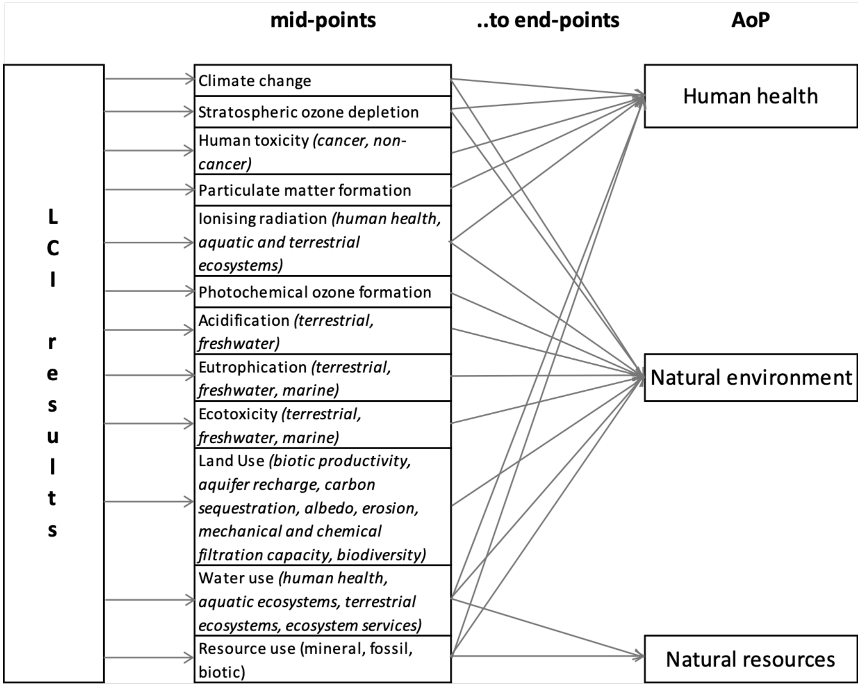


Figure 2.4 - ILCD framework for midpoint and endpoint levels of impact assessment.

Therefore, the same list of impact categories as for midpoint indicators applies to endpoint indicators but with a further distinction regarding which of the three AoPs are affected (e.g. stratospheric ozone depletion usually has one midpoint indicator, but two endpoint indicators, one for human health and one for natural environment):

- Climate change
- Stratospheric ozone depletion
- Human toxicity
- Particulate matter formation
- Acidification
- Ionising radiation
- Photochemical ozone formation
- Eutrophication
- Ecotoxicity
- Land Use
- Water use
- Resource use

All endpoint indicators related to a given AoP share the same unit and their contribution can be summed up and give an overall impact score per AoP (with or without weighting). When using midpoint indicators, aggregation and contribution analysis of different impact categories are only doable after normalisation and weighting.

Midpoint and endpoint indicators shouldn't be considered as two distinct parallel ways to choose from. Performing an LCIA on both midpoint and endpoint level is a viable option when they are functional to complement each other output respectively (i.e. in ILCD method) and it is in some cases necessary for supporting the interpretation of the results obtained.

2.2.5.5 Normalisation

In the normalisation step, the characterisation results are linked to the magnitude of impact, in a defined geographical region or sector, for each impact category. The aim of this step is to permit the comparison of the entity of the impact of the system under study across different impact categories. It can be performed at both midpoint and endpoint level. After normalisation, the output of the LCIA brings out information on how large or small the impact of the considered product system is, compared to the reference system.

Typically, the reference systems taken as bases for the normalisation can be either external or internal:

- Internal
  - Geographical areas (global, continental, regional or local)
  - Population of a given geographical area
  - Industrial sector
- External
  - Industrial sector
  - Other baseline references (a product system)

The normalised impact (*NI)* is calculated by multiplying the impact of the product system by the normalisation factor (*NF*):

$$NI_i = Impact_i * NF_i$$

where *i* is the considered impact category.

Normalisation factors are usually expressed in impact per person equivalents (*P,* representing the reference region) per year:

$$NF_i = \left(\frac{\sum_j (CF_j * E_j)}{P}\right)^{-1}$$

Where, i is the considered impact category and j are the elementary flows of the reference system.

The normalisation factors must pertain to the same methodology chosen for the LCIA. In other words, normalisation is coherent only if the methodology behind the calculation of the normalisation factor used is the same one used for the assessment of the product system.

Caution is required when applying normalisation. As there is no objective right choice of the reference system, the results of the LCIA, post normalisation, can be easily misinterpreted.

The reference system must be selected with due considerations as it may change the output of the assessment. Generally:

- the larger is the reference system, the lesser is the risk of introducing biases in the comparison
- the weight of the normalised results is not always representative of their importance.

To minimize the introduction of bias in the assessment, all the interventions of the product system should take place in the same geographical area as those of the reference system. This is to avoid that part of the assessed contributions derives from areas outside the reference system. With these due precautions normalisation is a useful way to express the different impacts on a common scale and this allows the practitioner to spot modelling errors leading to excessively high or low impacts in some impact categories, as the results are given per person equivalent.

2.2.5.6 Weighting

Weighting is performed with the scope of levelling the importance of the impacts coming from the normalisation step. It can only be used once the impacts have been normalised. The impacts are prioritised by assigning different or equal *weighting factors* to each impact category. It is essential to note that the criteria used for the weighting have no scientific bases, which means that this step is merely subjective.

This step can be useful for comparing across impact categories or giving results in a form that underlies prioritisation of ethical values.

2.2.5.7 Grouping

This step is focused on aggregating the impact categories into groups in order to make the output of analysis more readable and understandable. Examples of groups or cluster can be *global/regional/local impacts* or *impacts with high/medium/low priority*. The grouping generally consists in applying two methods:

- Sorting and clustering midpoints impact categories on a geographical basis
- Ranking the impact categories according to a defined hierarchy of priority

2.2.5.8 Impact categories

Impact categories refer to specific categories of impacts considered in a LCA study. These are generally related to resource use, emissions of environmentally damaging substances (e.g., greenhouse gases and toxic chemicals), which may as well affect human health. Impact assessment methods use models for quantifying the causal relationships between the material/energy inputs and emissions associated with the product life cycle and each impact category considered. Each category hence refers to a certain stand-alone impact assessment model.

The purpose of impact assessment is to group and aggregate the data according to the respective contributions to each impact category. This subsequently provides the necessary basis for interpretation of the results relative to the goals of the study (for example, identification of supply chain "hotspots" and "options" for improvement). The selection of impact categories should therefore be comprehensive in the sense that they cover all relevant environmental issues related to the product supply chain of interest.

Table 2.2 - List of the impact categories and indicators considered in the ILCD/PEF impact category method[72].

Impact categories	Impact assessment model and source	Indicator
Acidification	Accumulated Exceedance [74,75]	mol H$^+$ equivalent
Climate change	Bern model – Global Warming Potentials (GWP) over a 100 years time horizon. Intergovernmental Panel on Climate Change, 2007	kg CO_2 equivalent
Ecotoxicity, freshwater	USEtox model[76]	Comparative Toxic Unit for ecosystems (CTUe)
Eutrophication, Aquatic, freshwater	EUTREND model[77]	kg P equivalent
Eutrophication, Aquatic, marine	EUTREND model[77]	kg N equivalent
Eutrophication, terrestrial	Accumulated Exceedance[74,75]	mol N equivalent
Human toxicity, cancer effects	USEtox model[76]	Comparative Toxic Unit for humans (CTUh)
Human toxicity, non-cancer effects	USEtox model[76]	Comparative Toxic Unit for humans (CTUh)
Ozone depletion	EDIP model based on the ODPs of the worls Metereological Organization [78]	kg CFC-11 equivalent*
Particulate matter/ Respiratory inorganics	RiskPoll model[79,80]	kg PM2.5 equivalent
Photochemical ozone formation	LOTOS-EUROS model[81]	kg NMVOC equivalent**
Resource depletion, mineral, fossil	CML 2002[82]	kg Sb equivalent
Resource depletion, water	Water use related to local scarcity of water , Swiss Ecoscarcity model for water consumption[83]	m^3 water used (related to local scarcity water)

* CFC-11 = trichlorofluoromethane; ** NMOVC = non-methane volatile organic compounds

- Climate Change (CC)

  Climate change expresses the impact of greenhouse gases (GHG) based on the extent to which they increase the radiative forcing in the atmosphere. Out of the total of sunlight reaching the Earth's atmosphere, one fraction (around 28%) is directly reflected back into space by air molecules, clouds and the surface of the earth (particularly oceans and icy regions such as the Arctic and Antarctic) (albedo effect); the left out portion is absorbed in the atmosphere by GHG (around 21%) and the Earth's surface (around 50%). The latter heats up the planetary surface and is released back into the atmosphere as infrared radiation (black body radiation) with a longer wavelength than the absorbed radiation. This infrared radiation is partially absorbed by GHGs and kept in the atmosphere instead of being expelled into space. This is why the temperature of the atmosphere rises with the increase of the content of GHG in the atmosphere. The Global Warming Potential (GWP) of a substance is defined as the ratio between the increased infrared absorption it causes, and the infrared caused by 1 kg of CO_2:

$$GWP_{T,i} = \frac{\int_0^T a_i c_i(t)dt}{\int_0^T a_{CO_2} c_{CO_2}(t)dt}$$

where a_i is the radiative forcing per unit concentration increase of GHG i (W/m^2), $c_i(t)$ is the concentration of GHG i at time T after release (kg/m^3) and t is the time over which the integration is performed (year).

The GWPs have been developed by the UN Intergovernmental Panel on Climate Change (IPCC), and the list is updated periodically. The time horizon the GWPs are calculated for is variable, as the life spans of GHGs in the atmosphere differ from case to case (usually the integration time used is 20 or 100 years).

Table 2.3 - Examples of impact indicator for GWP impact category.

Substance	**Molecule**	**Atmospheric lifetime [years]**	**Radiative efficiency [W/m^{2}ppb]**	**GWP [kg CO_2-eq/kg GHG]**	
				20 years	*100 years*
Carbon dioxide	CO_2		1.37e-05	1	1
Methane	CH_4	12	3.63e-04	84	28
…	…	…	…	…	…

- Ozone Depletion (OD)

Ozone layer depletion refers to the thinning of the stratospheric ozone layer caused by a number of chlorinated and bromated substances, such as chlorofluorocarbons (CFCs) and halons.

Ozone (O_3) is an harmful pollutant in the lower atmospheric layers (tropospheric, ground-level ozone), but it is an essential substance in the upper atmosphere (stratospheric ozone) as it screens out more than 99% of the energy-rich UV (UV-B and UV-C) radiation from the sun, preventing destructive amount of it from impacting on life on the Earth’s surface. UV-C is the most dangerous wavelength, but it is almost completely filtered; UV-B is of the most concern due to the ozone layer depletion. Depending on the exposure intensity and time to UV-B both human health and ecosystem integrity are affected. The ODP reflects the change in the stratospheric ozone column in the steady-state due to amount of emission of that substance relative to that of R-11 (trichlorofluoromethane) and it is calculated as follows:

$$ODP_i = \frac{\delta[O_3]_i}{\delta[O_3]_{R-11}}$$

where $\delta[O_3]_{i,R-11}$ represents the change in the ozone column for a given substance i or R-11.

The ozone depletion potentials were developed by the World Meteorological Organisation (WMO) and they are subjects to periodic updates.

- Resource Depletion (RD)

  Resource depletion addresses the problem of decreasing pool of resources, needed by humans from nature in order to sustain their livelihood and activities. Abiotic resources are those considered as 'non-living resources' such as iron ore and crude oil. In terms of future availability of a resource the issue is not the current extraction and use of the resource per se but the depletion or dissipation of the resource.

  There is still much debate about what the issue of concern of natural resources is and about how this should be addressed in LCIA[73]. Impacts resulting from resource use are often divided into three categories following the impact pathway:

  - Methods aggregating natural resource consumption based on an inherent property
  - Methods relating natural resource consumption to resource stocks or availability
  - Methods relating current natural resource consumption to consequences of future extraction of natural resources (e.g. potential increased energy use or costs).

  Among the second listed methods, CML-IA is one of the most widely used. The CML-IA method for characterisation of abiotic stock resources defines an Abiotic Depletion Potential, ADP with a characterisation factor based on the annual extraction rate and the reserve estimates. In Guinée et al. (2011)[84] only the ultimate reserves are included, but Oers et al., (2002)[85] defined additional characterisation factors on the basis of reserves and reserve base estimates. CML-IA using reserve base estimates is the method recommended in the ILCD Handbook for LCIA in the European context[72].

- Acidification

  Acidification quantifies the impact of acidifying pollutants, notably SO_2, NO_x, HCl and NH_3 (that are mainly coming from combustion processes in thermal power plants, combustion engines, and waste incinerators). Rain, fog and snow trap and deposit the atmospheric pollutants. Furthermore, fallout of dry acid particles and aerosols is converted to acids when they dissolve in surface water or contact moist tissues (e.g. in the lungs). Examples of impacts are fish mortality in lakes (e.g Scandinavian lakes in 1990s), leaching of toxic metals from soil and rocks, and damage to forest and to buildings and monuments.

The acidification potential depends both on the potency of the emitted gas and on the sensitivity of the receiving environment in terms of buffering capacity of the soils and sensitivity of the ecosystems to acidification as expressed by their critical load.

- Eutrophication

  Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N), and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. High nutrient concentrations may also render the surface waters unacceptable as a source of drinking water. The indicator representatives of this category in the Nutrient Enrichment Potential, measured in kg of PO_4 equivalent.

- Photochemical Ozone Formation (POF)

  Photo-oxidant facilitates the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These reactive compounds may be injurious to human health and ecosystems and may also damage crops. Photo-oxidant may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx). The impact associated with this category is measured in kg of ethylene equivalent.

- Ecotoxicity and Human Toxicity Potential (EcoTOX and HT)

  Today’s toxicology science adheres to the principle that the dose is the factor differentiating a poison from a remedy. As consequence any substance emitted may imply toxic impacts depending on the following factors: emitted quantity (determined in the LCI), mobility, persistence, exposure patterns and bioavailability and toxicity. The latter four are considered by the characterisation factor (CF).

$$FF * XF * EF = CF$$

  - Fate factor (FF) describes the transports phenomena occurring after the pollutant has been emitted. It accounts the multimedia transport between the environmental compartments (air, soil, water, run-off system, etc.)
  - Exposure factor (XF) is the contact between a target organism and a pollutant over an exposure boundary for a specific duration and frequency
  - Effect factor (EF) relates the quantity of pollutant emitted to the probability of adverse effects

Depending on the target ecosystem or organism of interest the toxicity indicators can be divided into fresh water (FAETP), marine water (MAETP), terrestrial (TETP) and human toxicity potentials.

2.2.6 INTERPRETATION

Once the LCIA results are ready, practitioners should be able to elaborate and interpret them, keeping in mind the goal of the study, the main assumptions, the possible errors and parameters bringing uncertainties, and the applied modelling principles.

Usually, the LCIA results are elaborated in order to perform a hotspot analysis, among the different life cycle stages considered, and then, going more in detail in every process of those stages. At the end, the hot spot analysis will give back which are the main contributors to the outcomes in terms of life cycle phase, processes and flows. As reported by Rosenbaum[86] "the presence of uncertainties of different types and from numerous sources in LCA results is a fact and ignoring them may be more detrimental than managing them in an integrated manner". In other words, ignoring all the uncertainties sources, such as primary and secondary data, modelling principles, assumptions etc., can mislead the interpretation of the results, especially when more scenarios are compared.

Before going ahead with the quantification of the errors, it is always recommended to carry out a completeness check[71], in order to check that all the information and data needed to ensure a correct interpretation are "available and complete". As written in the ISO, in case information and/or data are missing or partially missing, it must be verified if that information is necessary or not to satisfy the goal and scope of the LCA. If necessary, the information should be retrieved, or the goal and scope should be modified, and adjusted. Otherwise, if the information results to be unnecessary, that should be justified and recorded.

Once the completeness is checked, the ISO recommends a sensitivity analysis for understanding the effect of the input uncertainties on the outcomes, however it does not suggest any kind of technique for doing this[87]. In addition to that, uncertainty analysis is employed to define the range or interval of confidence of the results.

The two analyses can be applied both for the LCI and the LCIA phases.

2.2.6.1 Sensitivity analysis

Generally, sensitivity analysis is employed in comparative studies, or in studies with different possible scenarios, in order to identify the parameters carrying the highest impact on the final results.

To achieve these results, several input parameters are identified and made to vary one at a time between a range of values, which can be defined by the two extreme percentiles of a statistical distribution or minimum and maximum values.

Starting from the hotspot analysis and the scientific judgment of the practitioner, several key parameters (energy and material flows) may be identified as the ones with the highest impact on the LCIA results. Then, as stated previously, one at a time the parameters are varied, and the results calculated. By analysing and comparing the results (LCIA outputs), it may be possible to define the parameters with the high influence on the LCIA outcomes, and specifically on which impact category they have the highest influence. Moreover, the results give hints on which parameters and flows should be considered and modified (when possible) in order to reduce the environmental impact of the system.[86]

In sensitivity analysis the inputs as well as the outputs are point values, and allows a rough comparison of the system since the results are not expressed with interval of confidence, and thus do not take in consideration the uncertainties.

2.2.6.2 Uncertainty analysis

Uncertainty analysis (or global sensitivity analysis) quantifies “how much each input parameter contributes to the output variance”[87].

The values required are the (probability) density functions of the input parameter selected. This function can have different distributions: normal, log-normal etc., which have to be always specified. Type of distribution, standard deviation, arithmetic mean, mode and median are information required to analyse the uncertainty. Typically, the uncertainty range used is the 95% interval (2.5th and 97.5th percentiles) of the distribution, that is the uncertainty range within the 95% of the randomly measures that can be found[86].

Amongst the several methods to quantify the uncertainty in LCA, the most used are: semi-quantitative pedigree matrix approach (used in Ecoinvent database to quantify variability and uncertainty of LCI data); Monte Carlo simulation used in almost all the LCA software, and the Taylor series expansion.[86]. Monte Carlo simulation is the method used in almost all the more diffused LCA software. It is based on the repetition of model calculations, generating samples of random values for all the variables, within the given probabilistic distribution. Then using those values the software estimates the LCIA outputs, in the form of probabilistic distribution, giving back as outcomes: arithmetic median, standard deviation, mode and median values. When Monte Carlo simulation is performed, particular attention has to be paid to the choice of the parameters selected: they have to be independent to each other, meaning they have to vary independently. Moreover, to get a higher accuracy the repetition of the model calculations (iterations) should be very high, the higher they are, the higher is the accuracy of the outcome.

At the end of the simulation and after some statistical analysis, such as the calculation of the 2.7th and 97.5th percentile, the results would be expressed as a range of values, *central value ± interval of confidence*. Combining sensitivity and uncertainty analyses would give a more accurate picture about the potential results, and qualitative and quantitative information on which elements of the product would require to be improved and modified in design phase to get better environmental performance.

2.3 THE EVOLUTION OF LCA METHODOLOGY OVER TIME

LCA is developing fast and dynamically incorporating the ever-changing necessities of society. LCA is booming in multiple directions: end-goals, applications, structure and depth. A splendid review of the history of LCA methodology, was published in 2011 by Guinée et al.[84]. Building upon their findings, the next sections will explore the evolution of LCA over the years, from the dawn of the methodology in the early 1970s, trying to understand cause and effects of the changes of the methodology, and identify its future developments.

2.3.1 THE BIRTH (1970-2000): FORGING THE LIFE CYCLE THINKING

The first studies that we now recognise as Life Cycle Assessments date back to the late sixties and early seventies, a time remembered by many for the oil crisis and the energy debate. The main driver behind the first LCA studies, however, was an earlier and less remembered environmental debate associated with wasteful resource use[88]. As a matter of fact, the first LCA studies were all focussed on packaging and waste management; these were then known as resource analysis, resource and environmental profile analysis, ecobalance and ecoprofile[89]. The oil crises were also instrumental in developing and spreading the LCA concept. The combination of the debate on wasteful resource use and energy is probably the main reason as to why LCA came to be such a comprehensive methodology.

The first well-known LCA study was conducted in 1969 in the US for Coca-Cola by the Midwest Research Institute[44,90–92]. The company was looking at a number of issues related to packaging, including alternative beverage containers (plastic bottles, refillable glass bottles and disposable container) and environmental consequences of package manufacturing. One of the most interesting outcomes of the study was that the company switched from glass to plastic bottle: a radical idea because at the time plastic had the reputation of "villain". Besides the Coca-Cola study, other independent initiatives can be identified around the same time: in the UK Ian Boustead constructed a simple LCA case study around milk packaging when writing a teaching text[90]; in Germany the Federal Ministry of Education and Science commissioned a study to elucidate the role of plastics in the growing problem of packaging[93]; in Sweden LCA studies were inspired by Tetra Pak intention to introduce a PVC bottle, which was hashly criticised not only because it was disposable, but also because it was an important source of acidifying substances when burnt in incinerators[44].

In the wake of the first studies, the LCA approach gained momentum and the concept spread quickly within the packaging industry and amongst policy makers on waste management; and the energy crisis added further interest in the energy part of the analysis[94]. In industry, new LCA studies came about for reasons related to competition between industries and marketing. In the early eighties and onwards, the LCA approach expanded from primarily internal corporate decision-making towards the domain of public debate as environmental issues became more than ever of public interest; this was driven by massive environmental disasters such as the chemical accident in Bhopal, India (1984), the nuclear reactor explosion in Chernobyl (1986) and the oil spill from the tanker Exxon Valdez (1989). The early methodology was a rather distant relative of today's LCA: it was not standardised; environmental impacts were quantified in terms of energy and material resource consumption and the amount of waste produced; and only a limited amount of emissions was reported. The first form of impact assessment was introduced in 1984: the Critical Volume approach reported the volume of air or water needed to dilute emissions to harmless level[95].

The period 1970-1990 comprised the decades of conception of LCA with widely diverging approaches, terminologies, and results. There was a clear lack of international scientific discussion and exchange platforms for LCA. During the 1970s and the 1980s LCAs were performed using different methods and without a common theoretical framework. LCA was repeatedly applied by firms to substantiate market claims. The obtained results differed greatly, even when the objects of the study were the same, which prevented LCA from becoming a more generally accepted and applied analytical tool[96].

It is in the 90s that LCA was recognised "as one of the most important tools for decision-making in the field of environmental management"[97] when the idea that environmental protection should go beyond end-of-pipe strategies and emissions control to optimisation of product systems gained support. LCA was then an appealing tool: it was product-oriented, quantitative (and thus seemingly objective) and somehow structured. As the interest and use of LCA spread, also criticism towards the methodology increased. Critics claimed that LCA studies were often biased and used by product manufacturers who sponsored the study to promote their own product[98,99]. The main issue was that LCA methodology was not yet standardised; on the contrary, its application was quite subjective. This concern was the driving force behind the exceptional efforts directed at developing and improving the LCA methodology. The 1990s saw a remarkable growth of scientific and coordination activities worldwide, which is reflected in the number of workshops and other forums that were organized in this decade (e.g. World Wildlife Fund and The Conservation Foundation in Washington DC in 1990; SETAC-Europe in Brussels in 1992, etc.) and in the number LCA guides and handbooks produced (e.g. Environmental Assessment of products. Vol. 1: Methodology, tools and case studies in product development and Vol. 2: Scientific background; in 1998[100]). Also, the first scientific journal papers started to appear in the Journal of Cleaner Production, in Resources, Conservation and Recycling, in Environmental Science & Technology, in the Journal of Industrial Ecology, and in other journals. The field also developed its own journals, most notably the International Journal of Life Cycle Assessment.

In this period, the first scientific conferences on LCA were organized by the Society of Environmental Toxicology and Chemistry (SETAC); notably, SETAC was instrumental to the development of the LCA methodology with the first guidelines published in the Code of Practice[101]. The work on methodology development culminated with the standardisation of LCA by the International Organization for Standardization (ISO), which started in 1993 and terminated in 2002 with the publication of the 14040 series[102–106]. Furthermore, the work undertaken to develop the methodology led to the establishment of LCA as an academic subject.

2.3.2 THE PAST (2000-2010): DECADE OF ELABORATION

The first decade of the 21st century showed an ever-increasing attention to LCA. A sign of increasing research activity on LCA is the number of articles published in academic journals, which as shown in Figure 2.5, increased tenfold in 1990-1999 and 2000-2009.

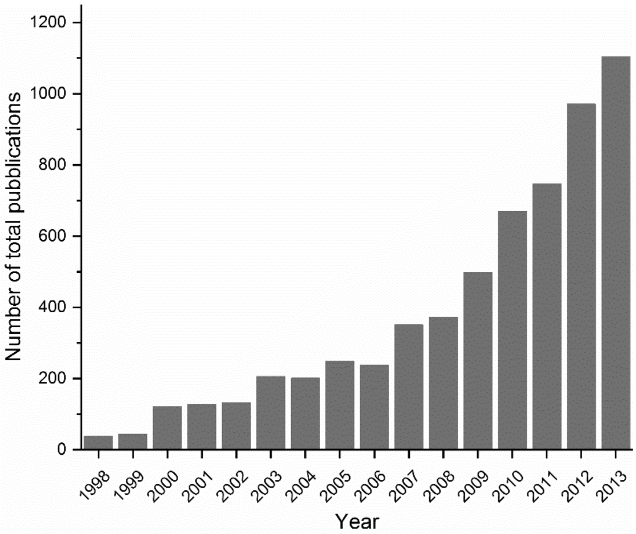


Figure 2.5 - Number of LCA articles per year (from Hou et al., (2015)[107]).

In 2002, the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) launched an International Life Cycle Partnership, known as the Life Cycle Initiative. The Life Cycle Initiative aimed at operationalising life cycle thinking and improving the supporting tools through better data and indicators. Furthermore, life cycle thinking continued to acquire importance in European Policy and being incorporated in different thematic strategies on the sustainable use of resources, and prevention and recycling of waste. The European Platform on Life Cycle Assessment was established in 2005, to promote the availability, exchange, and use of life-cycle data, methods, and studies for reliable decision support in public policy and in business. In parallel, in the USA, the U.S. Environmental Protection Agency (EPA) started promoting the use of LCA, and generally all over the world environmental policy got increasingly life-cycle based. Numerous life cycle-based carbon footprint standards started being established[108].

On the whole, the first LCA decade of the new millennium can be characterized as the decade of elaboration. The demand on LCA steeply increased, but a divergence in methods rose again. As a matter of fact, ISO never aimed at standardizing LCA methods in detail; as a result of this there is no general consensus on how to interpret some of the ISO requirements. Hence, different approaches have been developed with regards to system boundaries and allocation methods[67,109], dynamic LCA[110–113], spatially differentiated LCA[67,109], risk-based LCA[114–116], and environmental input-output based LCA and hybrid LCA[117–119]. Furthermore, life cycle costing (LCC[120]) - first used in the 1960s by the U.S. Department of Defense for the acquisition of high-cost military equipment[121] - and social life cycle assessment (SLCA[122]) approaches have been proposed, clashing in some cases[123,124] with environmental LCA (with respect to system boundaries, time perspectives, calculation procedures, etc.). These different approaches share the life-cycle basis, but differ in the elaboration of the methodology and in the goals. Notwithstanding numerous attempts and LCA textbooks[44,82,125] to clarify the integration of these new approaches into the standardized methodology, there was a further need for structuring this varying field of LCA approaches. To this end, projects like CALCAS in 2006 (Co-ordination Action for innovation in Life Cycle Analysis for Sustainability) were commissioned by EU, resulting in interesting outcomes[126]. One of its main results was the definition of Life Cycle Sustainability Analysis (LCSA), a transdisciplinary framework of methods and broadening the assessment to include social and economic impacts.

2.3.3 THE PRESENT AND THE FUTURE: TOWARDS PROSPECTIVE ASSESSMENTS

Over time, the guidance that was provided by the LCA manuals and ISO standards has been typically applied to modelling and assessing environmental impacts in an ex-post fashion, meaning after products or technologies have been commercially in use for extended periods of time and information and data are available from empirical experience. The majority of LCA studies were, in fact, retrospective as they were performed after commercial-scale production according to directives set by regulatory agencies. Such analyses were useful for informing consumers and regulators about the environmental impacts of a product (e.g.

carbon footprints and ecolabeling), yet had limited ability to reorient technology trajectory because temporal delays and large capital investments contribute to technology lock-in[127].
A new concept of LCA started developing, as opposed to retrospective LCA, sustaining that the ISO standard could and should also be used when LCA is applied in an ex-ante manner. Ex-ante is defined as before a product or technology is commercially deployed at scale (Tecchio et al., 2015[128]) and information and insights on the topic under assessment are not (yet) readily available. Some of these challenges have been identified long ago. Frischknecht et al. questioned the fitness of standard LCA to assess the potential impacts of future technologies already in 2009[83]. However, these challenges remained unaddressed for a long time, until recently some studies started to come out attempting to define and apply the concept of prospective assessment. In fact, there have been some attempts to prospective LCA that employs modelling tools requiring less accurate data sets and that focus analyses on potential environmental impacts arising from R&D decisions. Drawing from diverse fields ranging from future studies to thermodynamics, published advances included the incorporation of backcasting[8], foresight tools, and scenario development into LCA and material-flow analysis[9–15], dynamic LCA process modelling[16], and stochastic decision analysis[17–19].

2.3.3.1 Backcasting method

According to Hertwich et al.[8], LCA must promote and achieve sustainable consumption and production, but it has been little used. In their view, the questions that one needs to answer when addressing sustainable consumptions - who causes how much of which impact and how consumption patterns can be changed to reduce these impacts - require an analysis that extends beyond traditional LCA. This includes the combination with input-output analysis, the use of consumer expenditure data, and the analysis of trade. A systematic extension in this direction, according to them, can go further than energy analysis has gone: changes or differences in consumer expenditure can be observed in panel studies of sustainable consumption measures; income elasticities and cohort effects can be measured and used in scenario analysis. Their work also described how life-cycle methods can be used to conduct prospective and ex-post evaluations of sustainable consumption and production measures. The methods described in their work indicates LCA needs to be combined with economic and sociological investigations to be useful as a tool for sustainable consumption. Finally, Hertwich et al. underlined that even though a further method development and data collection is advisable, efforts should focus on developing and testing new research designs that are directly relevant to policy making.

2.3.3.2 *Scenario development*

Pesonen et al.[9] highlighted in their work that scenarios are in one way or another an integral part of any LCA, and should integreate the assessment depending on the applications of the LCA (as shown in Figure 2.6).

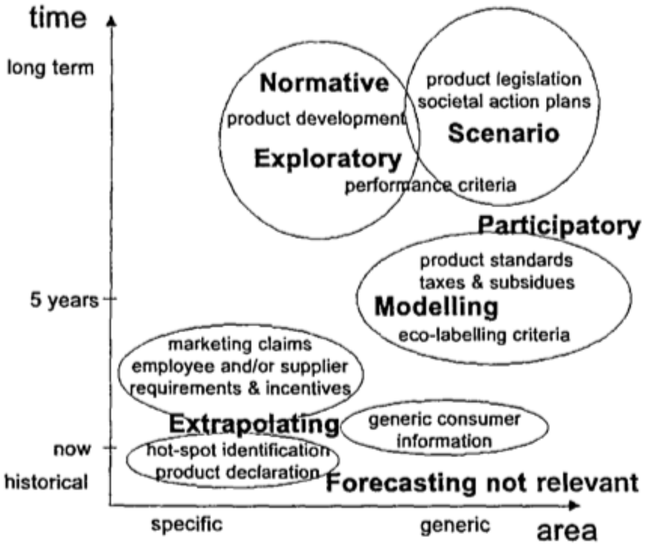
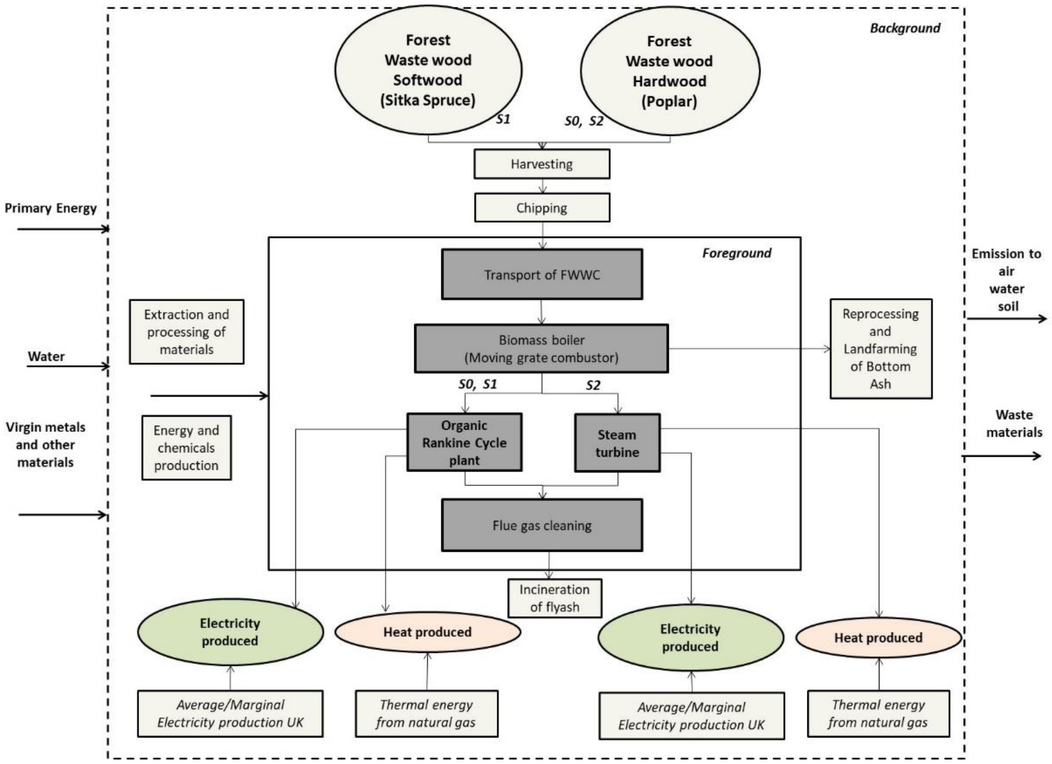


Figure 2.6 - Relevance of different future research methods in relation to applications of LCA[9].

These, however, are not always dealt with explicitly and at the time of their work there had been no general LCA framework or procedure available on the systematic development of scenarios for new technologies. To deal with these issues, the Working Group 'Scenario Development' in LCA of SETAC-Europe was founded. In the first phase the Working Group examined how and for what reasons different scenarios are developed for an LCA study. As a conclusion of the first phase, the group suggested two basic approaches for scenario development in LCA studies: Cornerstone and What-if scenarios that Pesonen et al. presented in their work. Specifically, What-if scenarios are used to compare quantitatively different alternatives in the system or to test some specific changes within the system. The Cornerstone scenarios are more fundamental and comparable to scenarios in future studies. An additional separating feature is that only a relatively small number of scenarios should be included in Cornerstone studies, whereas the What-if approach can include a large number of scenarios. In both cases, an important part of using scenarios is to provide a valid reasoning for selection of certain parameters. Pesonen et al. also tried to identify the subsequent phases that, in their view, should concentrate on the modelling issues of scenarios and on a review on case studies that have used scenarios and also reported them explicitly or implicitly. Consequently, they advocated that the final results of the Working Group should result in a framework or guideline possibly enhancing or expanding the standardisation documents of the ISO 14040 series.

In a work published in 2016[129], Tagliaferri et al. recognized that the transport sector is one of the most challenging sector when tackling emissions reduction. The development of technologies in the automotive industry, such as electric and fuel cell vehicles, were considered appealing solutions to potentially reduce greenhouse gases emissions; however, the process development requires an intensive use of scenario modelling in order to take into account the uncertainties and possible configuration of the life cycle of the latter technologies. In the study the authors presented a life cycle assessment of an electric passenger vehicle using a lithium-ion battery (BEV) and compared it to an internal combustion engine vehicle (ICEV) and hybrid vehicles. Firstly, the LCA methodology was used to predict the environmental impacts of the ICEV and BEV under different scenarios of future EU energy mixes. The results showed that the GWP was projected to decrease for both technologies but advanced processes for the manufacturing of biodiesel for ICEV and battery for BEV needed to develop further to reduce the toxicity impacts of both systems. Afterwards, two additional scenarios were subjected to analysis with regards to the disposal phase: a base scenario – high recycling rate - in which the vehicle fleet was totally assumed to be disposed in EU and, conversely, a low recycling rate scenario, in which the part of the vehicle fleet that leaves the EU was considered to be sent to landfill outside the EU. In this case, a negligible variation of the results was observed for the two cases and this highlighted how the disposal phase has a minor impact on the total environmental burden of the system.

Another study based on scenario development was published in 2018[130]; the focus of the study was the role of bioenergy in helping the UK meet its carbon target in 2050 and the European Renewable Energy Directive objectives for 2030. To this end, uncertainties were associated with the use of bioenergy, and whether or how much it contributes to green-house gas emission reductions. In response to this, and to help identifying environmental benefits and burdens associated with biomass use for energy production, an LCA was carried out on a biomass-fired CHP plant: the Heathrow Airport energy centre, able to process woodchips sourced from nearby forests providing electricity and thermal energy. In this paper, the authors made use of a scenario analysis to compare the impacts of the biomass plant against fossil alternatives and to identify which renewable energy sources, between biomass and MSW, needed to be prioritised for development and investment.



Scenario	Scenario Description
S.0	Baseline scenario for the Heathrow energy centre: thinned and chopped hardwood (i.e. Poplar) from the forest is transported to the Heathrow combustion and ORC plant to produce electricity and thermal energy.
S.1	Softwood (i.e. Sitka spruce) is used rather than hardwood in the Heathrow plant.
S.2	Hardwood forest residues are used to produce energy in a biomass boiler followed by a steam turbine
S.3	Electricity is produced by incineration of municipal solid waste. The LCA model is based on the North Hykeham incineration plant in the UK (Evangelisti et al., 2015) with landfilling as the reference system replaced.
S.4	Electricity is produced using hard coal, based on published data (Thinkstep, 2015).
S.5	Electricity is produced using natural gas according to Thinkstep (2015)
S.6	The UK electricity mix is considered according to Thinkstep (2015).
S.7	The 2030 UK electricity mix is considered, according to the National grid scenarios (National grid, 2014)

Figure 2.7 – List of scenarios and system boundaries for the Heathrow Airport energy centre, from Tagliaferri et al. (2018)[130].

The results showed a reduction in GHG emissions from using biomass, with further benefits if the bottom ash resulting from the biomass reactor is collected and re-used as a soil conditioner for land-farming or forestry. The overall account of the GHG emissions of the biomass plant showed a negative balance (thus a positive effect for the environment) when avoided burdens due to electricity and thermal energy production from more conventional technologies are considered. The study highlighted that the organic Rankin cycle installed at Heathrow results in a lower environmental impact compared to an alternative steam turbine scenario, because of the higher efficiency of the ORC system. Finally, the comparison with other renewables (i.e. municipal solid waste) and non-renewable sources (i.e. natural gas and coal) showed that while the biomass source results the best option for GHG emission savings, its impact can be higher for the categories related to ozone layer depletion due to ash disposal.

Further on the topic of waste to energy, Evangelisti et al. published in 2015[131] a life cycle assessment on the integrated use of gasification and plasma cleaning for the treatment of MSW and generation of energy. As the authors pointed out, in the past, almost all residual municipal waste in the UK was landfilled without treatment. In this study, a life cycle assessment was performed on a future plant using an advanced two-stage gasification and plasma technology able to thermally treat waste feedstocks to produce electricity, steam and a vitrified product. Two different scenario analyses were undertaken in the study. The first one aimed at quantifying the environmental impacts of the process under seven scenarios related to different types of feedstocks (municipal solid waste, solid refuse fuel, reuse-derived fuel, wood biomass and commercial & industrial waste) and therefore identify the process steps which contribute more to the environmental burden. A second scenario analysis was performed on key processes taken part to the life cycle of the system, such as oxygen production technology, metal recovery and the appropriate choice for the secondary market aggregate material. Through this approach to the assessment, the authors were able to conclude that the environmental impact changes on the base of the characteristics of the feedstock treated and it is not possible to identify a single waste stream which is better than the other for all the impact categories considered. Specifically, the refuse-derived fuel emerged as the lowest impacting feedstock in terms of both global warming potential and acidification potential. For all the other impact categories analysed, the two-stage gasification and plasma process showed a negative impact for all the waste streams considered, mainly due to the avoided burdens associated with the production of electricity from the plant. The authors underlined that the performance of the overall system depends primarily on the avoided burdens, i.e. on net electrical efficiency and recovery of usable ferrous and non-ferrous metals as emerged from the scenario analysis. Finally, it was underlined that the robustness of their conclusions was partially limited because the gasification and plasma process were not yet fully commercialised so that the analysis had to be based on pilot plant results and simulations.

Regarding the use of scenario in LCA, Spielmann et al.[10] emphasized that the objective of scenario modelling in LCI is to gain insight into the future development of LCI product systems. They claimed that various cornerstone scenarios may be used to identify the environmentally most robust option: in other words, having no high environmental impacts in any particular cornerstone scenario and comparatively low environmental impacts in most cornerstone scenarios. According to them, scenario modelling benefits from two basic principles of the LCI model. First, it is possible to explicitly distinguish between issues within the influence of the decision maker (foreground processes), e.g. technology options, and issues that cannot be directly influenced by the decision maker, but may influence the investigated options (background processes). Second, scenario analysis is performed on the unit process level to account for the heterogeneous nature of a product system. The distinction made between a scenario's socio-economic and technology components allows for the structured development and quantification of unit process scenarios and for increased transparency in a prospective LCA. In Spielmann et al.'s opinion, the structure of the model permits the re-use of the developed unit process scenarios in other studies (similar to the approach proposed by Fukushima et al.[132]), and is compatible with one of the most prominent LCI databases, 'ecoinvent'. The procedure they proposed was claimed to facilitate the generation of a small set of consistent and diverse cornerstone scenarios, representing the entire product life cycle. Also it would allow for the investigation of interesting, meaningful and varied future states of a system in a manner different from that proposed previously by Huijbregts et al.[133]. Spielmann et al. followed on arguing that the socio-economic component of each unit process scenario vector can be used for the generation of cornerstone scenarios. In contrast to unit process specific technology variables, socio-economic variables are of a more general nature and may be used as descriptors for more than one-unit process. Hence, in their view, no unit process specific knowledge and skill is needed to check the pair-wise consistency of the various levels of socio-economic impact variables. On the whole, scenario modelling was identified by Spielmann et al. as a viable way to provide an appropriate framework for combining various impact variables describing the future development of different unit processes and selecting a set of cornerstone scenarios. According to them, this can thus be regarded as a powerful tool for comprehensive uncertainty management in prospective attributional LCA.

A further attempt to prospective environmental assessment was made by Wender and Seager[11]. They recognized that LCA was the proper framework for understanding the environmental impacts of nanotechnologies. However, they found that, in practice, applying LCA to nanotechnology is problematic. The performance, emissions, and inventory data collected at the laboratory scale are usually not representative of the commercial scale. According to them, despite the high uncertainty, LCA may guide nascent technologies towards being environmentally beneficial through early identification of leverage points. Building upon these premises their research applied a novel LCA method based on laboratory-scale manufacturing data and battery performance modelling to quantify the energy trade-offs associated with nano-enabled lithium-ion batteries. As easily expected, they found out that extrapolating laboratory scale manufacturing data to commercial scales is a large source of uncertainty; they warned in fact that it is likely that the energy requirements of nanomanufacturing processes would decline with increased experience with nano-engineered materials and produce them on increasing scales. Historically, energy requirements of a variety of industrial manufacturing processes decrease asymptotically, often by several orders of magnitude, as the manufacturing rate increases. It thus requires substantial energy, material, and monetary investments at the lab scale in order to sufficiently develop nanomanufacturing processes to appreciate any returns to scale, and innovative research is directed towards developing high-rate processes. To this end, Wender and Seager stressed that applying LCA under uncertainty is problematic and requires simplifying assumptions which contribute to uncertainty in the results. Despite these obstacles, in their view, prospective LCA provides valuable information into likely problem areas for the scale-up of specific technologies. In their case study they combined battery performance modelling with lab-scale inventory data to quantitatively connect manufacturing and use phases. Their case study demonstrated both the challenge and value of prospective LCA. Ultimately, Wender and Seager underlined that their results can be useful to guide emerging technologies towards a reduction in overall environmental burden, and can be used to differentiate technologies based on their potential for large scale application.

A similar approached-based scenario was used by Dale et al.[13] in an attempt to model the future life-cycle greenhouse gas emissions and environmental impacts of electricity supplies in Brazil. The authors of this study combined life-cycle data for electricity production with scenarios developed ad-hoc to examine environmental impacts of future electricity generation under a baseline case and side cases. The calculation model was based on different data inputs, either originating from direct sources, regional statistics or from scenarios (as shown in Figure 2.8).

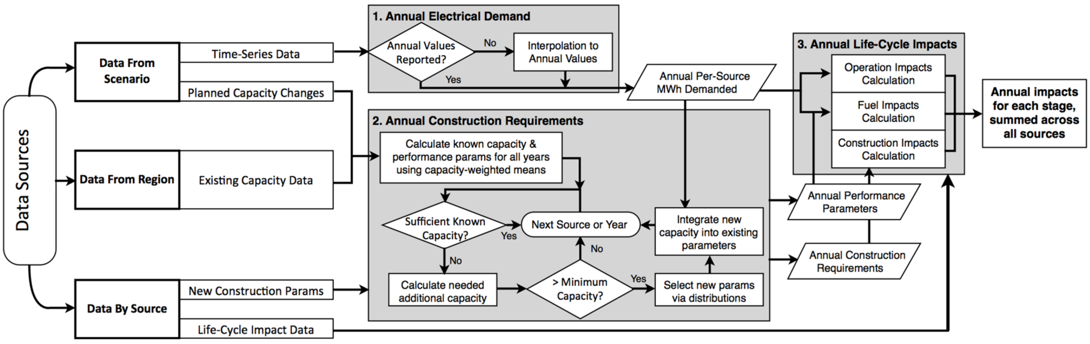


Figure 2.8 - Calculation model, used by Dale et al.[13], based on scenario development for the environmental impacts of electricity supplies.

Through this approach, the authors were able to estimate the future environmental impact arising from the adoption of different electricity mixes. However, Dale et al.[13] highlighted the need for future works to focus on some aspect of the life cycle that lacked sufficient level of information in the LCI, hence adding uncertainty to the environmental impacts calculated in the study.

In another attempt to use LCA for forecasting the environmental performances of new technologies, Eckelman et al.[12] calculated the environmental impacts of carbon nanotubes (CNT). Starting from the assumption that the environmental impacts of nanomaterials arise both from releases of the nanomaterials themselves as well as from their synthesis, they employed a LCIA model (USEtox model) to quantify and compare aquatic ecotoxicity impacts over the life cycle of CNTs. Using an approach based on the use of scenarios to understand the future implications of the use of CNTs. Specifically, they assumed that the parameters for evaluating CNT ecotoxicity are bounded by a highly conservative "worst case" scenario and a "realistic" scenario that draws from existing literature on CNT fate, transport, and ecotoxicity. Through this approach, Eckleman et al. were able to show that the ecotoxicity impacts of nanomaterial production processes were roughly equivalent to the ecotoxicity of CNT releases under the unrealistic worst-case scenario, while exceeding the results of the realistic scenario by various orders of magnitude. Furthermore, the uncertainty that existed for both production and release stages was taken into account using a combination of uncertainty and scenario analysis. The results of their analysis underscored the contributions of existing work on CNT fate and transport, as well as the importance of life cycle considerations in allocating time and resources toward research on mitigating the impacts of novel materials.

2.3.3.3 Material-flow analysis

Material-flow analysis was used by Simon and Weil[14] to evaluate the feasibility of using lithium-ion batteries as energy storage for power systems, grid support and electric mobility. Experiments and first use experiences showed their potentiality in various applications. However, the environmental impacts of battery production, use and recycling were not well understood. To understand better the ecological properties of these batteries, material and energy flow analysis was conducted. The latter defines the possible sources and consumers of relevant materials, substances, pollutants and energy flows. To this end, Simon and Weil's study analysed the consumed materials and energy as well as the emitted substances and waste heat of different lithium-ion batteries. Through material and energy flow analysis they focused on the production phase and included active and passive components and material and on energy consumption as well, in order to capture the consequences of employing the batteries in different applications, and hence driving the decision-making process.

In a work on fully electric vehicles, Zimmermann et al.[15] advocated with strong impetus the use of time-resolved LCA (trLCA) as a better tool than scenario analysis when calculating future environmental impacts. Time-resolved LCA (trLCA) was previously described by the same authors "as an LCA approach which is based on statistical time-resolved data". This method was claimed to respect the dynamic developments in a product's surroundings. In their work, no statistical data - in terms of empirical, descriptive statistics - was available for potential future developments. As an alternative, Zimmermann et al. drew on an evaluation of future-oriented scenarios to obtain prospective data for trLCA. In their view, trLCA turned out to be in any case the more robust calculation approach, if enough data is available or the static LCA is created from the same data set, because it takes higher resolution data and dynamic developments into consideration.

The claimed robustness of trLCA for assessing long use phases with regard to any type of development is however limited by the quality, LCA conformity, and resolution of the scenarios used. The general recommendation resulting out of their work is that, unless direct cooperation with the scenario makers is possible, any type of scenario modification for LCA leads to the irresolvable question of whether the applied modifications are legitimate. Therefore, for the prospective comparison and LCA-based decision making for products or production systems, it is essential to take the most plausible LCI data sets available into consideration to calculate fair LCA results.

2.3.3.4 *Dynamic LCA process modelling*

A different approach to the prospective assessment of environmental impacts involves the so-called dynamic life cycle assessment (DLCA). In brief, DLCA is an approach to LCA which explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems. A conceptual overview of the DLCA is reported in Figure 2.9.

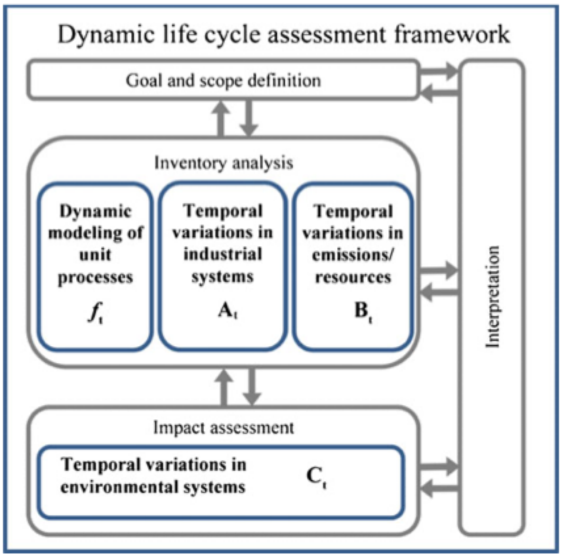


Figure 2.9 - Conceptual diagram of dynamic LCA framework[16].

In order to illustrate the potential importance of this method, Collinge[16] used a simplified case study of an institutional building. Previous LCA studies consistently found that energy consumption in the use phase of a building was dominant in most environmental impact categories. However, due to the long lifespan of buildings and potential for changes in usage patterns over time, a shift toward DLCA was suggested by the author. A simplified mathematical model was used to incorporate dynamic information from the case study building, temporally explicit sources of life cycle inventory data and temporally explicit life cycle impact assessment characterization factors, where available. The DLCA model was evaluated for the historical and projected future environmental impacts of an existing institutional building, with additional scenario development for sensitivity and uncertainty analysis of future impacts. In Collinge's work, the results showed that overall life cycle impacts varied greatly in some categories when compared to static LCA results, generated from the temporal perspective of either the building's initial construction or its recent renovation. In the future scenario analysis, the baseline DLCA scenario showed also a variation in all impact categories compared with the static LCA. On the whole, the findings of Collinge's work supported the use of dynamic modelling in life cycle assessment to increase the relevance of results. Given that temporal changes are rarely accounted for in LCA practice, it emerged clearly that LCA could be improved by incorporating a more dynamic focus.

2.3.3.5 Stochastic decision analysis

A novel approach to LCA of emerging technologies, opened the gate to a series of studies on new technologies. This approach explored the possibility of considering in the assessment multiple criteria of weighting and normalising the results of the assessment in order to either anticipate potential changes of the decision-criteria of stakeholders or face multi-stakeholder situations.

Prado-Lopez et al.[19] underlined that comparative LCAs usually lack robust methods of interpretation that help decision makers understand and identify trade-offs in the selection process. In their view, truncating the analysis at characterization is misleading and existing practices for normalization and weighting tend to oversimplify important aspects of a comparison. To this end, they adopted in their work a stochastic decision approach called stochastic multi-attribute analysis for life-cycle impact assessment (SMAA-LCIA) that "used internal normalization by means of outranking and exploration of feasible weight spaces". In their view, opposed to conventional approaches, SMAA-LCIA was capable of exploring high uncertainty in the input parameters, normalizing internally by pair-wise comparisons (outranking) and yielding probabilistic, rather than discrete, comparisons that reflect uncertainty in the relative performance of alternatives. To demonstrate the validity of the selected method they focused on a case study comparing liquid and powder laundry, using three approaches to normalization and weighting: (1) characterization with internal normalization and equal weighting, (2) typical valuation consisting of external normalization and weights, and (3) SMAA-LCIA using out-ranking normalization and stochastic weighting. The result of Prado-Lopez's study showed that all three methods favoured univocally one product. However, each method resulted in different conclusions regarding the environmental trade-offs, and according to the authors this outcome avoided the bias introduced by typical evaluation that are oversimplified and focused only on a few impact categories due to the use of normalization references.

Following a similar approach, based on SMAA-LCIA, Linkov et al.[134] and Canis et al.[17] investigated the synthesis process of single-walled carbon nanotubes. The driver in that case was a general uncertainty associated with engineered nanomaterials that called for the need for research regarding their potential environmental consequences. However, rather than focusing the output of the analysis on decision-makers such as regulatory agencies, product developers, or other nanotechnology stakeholder - as in the case of other stochastic decision analysis techniques - they extended the focus on technology performance. Four different synthesis processes were compared based on five different performance criteria. One of the main findings of the work was that the incorporation of stochastic decision analysis techniques like SMAA- LCIA enables explicit uncertainty analysis and makes a decision model especially suitable for cases where information to evaluate criteria scores is limited, as well as to handle multi-stakeholder situations with varying preference information on criteria weights. Another revealing aspect of their study was that uncertainties exist both in the domain of performance assessment and in the domain of decision-maker or stakeholder preferences. In their view, only by exploring the sensitivity of the decision outcome to all types of uncertainty in concert can those with the greatest influence be discovered, as uncertainties in one aspect of the analysis may overwhelm those in other areas that may have otherwise been considered important areas to investigate further. In fact, the authors advocated that the overall results of this process would translate in a better understanding of the sensitivity of the system to important design variables or parameters, a reprioritization of research and development efforts, a better understanding of decision-maker preferences, better decisions, and ultimately, environmentally advantageous technologies.

2.4 LCA OF EMERGING TECHNOLOGIES

2.4.1 MULTIPLE DEFINITIONS, ONE GOAL

Over the past recent years there have been numerous attempts to define a methodology for the assessment of new technologies, and coin a unified term to univocally identify this approach. However, these attempts have contributed to render even more unintelligible the identification of such approach to LCA. There exist in fact several definitions and proposed methods in the literature that aim at the same objective. In the author’s view, the most comprehensive description of LCA applied to new technology has been proposed by Cucurachi et al.[135]: “performing an environmental life cycle assessment of a new technology before it is commercially implemented in order to guide R&D decisions to make this new technology environmentally competitive with the incumbent technology mix". This definition embraces virtually all the study published so far on this topic. On the other hand, after coining such definition, Cucurachi et al. followed on with a further attempt to unify these studies under the same term, namely "ex-ante LCA". As a result of this, an additional term was added on top of the already high pile of "forward-oriented" LCA's names, making very difficult to "digest the alphabet soup of LCA"[136]!

Figure 2.10 - "The alphabet soup of LCA", a rhetorical view (by Guinée et al.[136]) on the numerous types of LCA proposed over the years.

A lesson learned, and hence in this Thesis there will be no effort in coining an additional term. On the other hand, such numerous bids to define a methodology have contributed over the year to filter out non-successful attempts and bring to present a series of publications that can be used as guidelines when performing an LCA on emerging technologies. To this end, a selection of "forward-oriented" LCAs available in the literature is reported and categorised by type of assessment in Table 2.4, along with a brief description of the latter.

Table 2.4 - Literature on "forward-oriented" LCA studies (from Cucurachi et al.[137]).

Type of assessment	Definitions or descriptions given in literature
Prospective LCA	"An LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g. small-scale production), but the technology is modelled at a future, more-developed phase (e.g. large-scale production)" (Arvidsson et al., 2017[138]). Prospective LCA integrates forecasting methods in its approach (Hummen and Kastner, 2014[139]). See also (Mendoza Beltran et al., 2018[140]; Miller and Keoleian, 2015[141])
Dynamic LCA	"The analysis of individual technologies must consider the extremely dynamic development. This concerns the development of products and their production processes as well as their technical performance and the development of background systems." (Pehnt, 2006[142]) This approach focusses on including the dynamics of parameters that are expected to change over time and to compare different development pathways (Alfaro et al., 2010[143]).
Anticipatory LCA	Takes a forward-looking (not retrospective assessment) and engages stakeholders to inform critical modelling decisions and increase credibility and relevance of results. Anticipatory LCA can be defined as "non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology." The aim is to identify the most relevant uncertainties and engaging research and development decision makers to guide research and development and innovation. (Wender et al., 2014[4]).
Ex-Ante LCA	In ex-ante LCA an environmental analysis of a technology that is typically still in its R&D phase is performed (Hesser et al., 2017[144]; Schrijvers et al., 2014[145]; Tecchio et al., 2015[128]) to guide R&D. Villares (Villares et al., 2017[146], 2016[147]) stresses the ex-ante application of LCA, meaning before (ex-ante) market introduction (Roes and Patel, 2011[148]).
Consequential LCA	Consequential LCA provides understanding on "the potential effects of policies on market responses to support environmental decision making" (Kätelhōn et al., 2016[149]). "[T]o provide information on the environmental burdens that occur directly or indirectly as a consequence of a decision (usually represented by changes in demand for a product)" (Guinée et al., 2018[136]).
Lifecycle sustainability analysis (LCSA)	Life cycle sustainability analysis proposes a transdisciplinary framework of methods and in principle broadens the assessment to include social and economic impacts, and therefore include more than just technological relations e.g. by scaling up the technology to society wide implementation. This may imply making future scenarios, but not necessarily looking into innovative technologies (Guinée et al., 2011[84]; Hu et al., 2013[150]; Van Der Giesen et al., 2013[151]).

2.4.1.1 Prospective LCA

In their work, Arvidsson et al., 2017[138], recognized that the challenge of assessing emerging technologies with life cycle assessment had been increasingly discussed. In light of this, they proposed a definition of prospective LCA: an LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g., small-scale production), but the technology is modelled at a future, more-developed phase (e.g., large-scale production). Following on this, the authors suggested that methodological choices in prospective LCAs must be adapted to reflect the goal of assessing environmental impacts of emerging technologies, which deviates from the typical goals of conventional LCA studies. Their recommendations stemmed from a review of selected prospective LCA case studies, mainly from the areas of nanomaterials, biomaterials, and energy technologies as listed in Table 2.5.

Table 2.5 - Prospective LCA studies reviewed by Arvidsson et al., 2017[138].

Case study	Emerging technology studied
Arvidsson et al. (2014)[152]	Graphene production
Arvidsson et al. (2015)[153]	Nanocellulose production
Bergesen and Suh (2016)[154]	Cadmium telluride photovoltaics
Caduff et al. (2012)[155]	Large wind power turbines
Delgado-Aguilar et al. (2015)[156]	Nanocellulose-enforced paper
Edwards et al. (2014)[157]	Automotive fuels
Gavankar et al. (2014)[38]	Carbon nanotubes
Gibon et al. (2015)[158]	Concentrating solar power
Healy et al. (2008)[159]	Carbon nanotube production
Janssen et al. (2014)[160]	High-gravity ethanol production from wheat straw
Janssen et al. (2016)[161]	High-gravity ethanol production from wood chips
Kushnir and Sandén (2008)[162]	Fullerene and carbon nanotube production
Li et al. (2013)[163]	Nanocellulose production
Liptow et al. (2015)[164]	Ethylene production from wood
Manda et al. (2014)[165]	Membrane filtration system for drinking water
Manda et al. (2015)[166]	Nano-silver T-shirt
Nordelöf et al. (2014)[167]	Electric vehicles
Pini et al. (2017)[168]	Self-cleaning float glass
Pizza et al. (2014)[169]	Graphene nanocomposites
Roes and Patel (2011)[148]	Caprolactam production
Shen et al. (2012)[170]	Plastic materials
Walser et al. (2011)[171]	Nano-silver T-shirt
Yao et al. (2015)[172]	Ethylene production
Zimmermann et al. (2015)[15]	Electric vehicles

As a result of the reviewed publications, Arvidsson et al. found of crucial importance to include technology alternatives that are relevant for the future in prospective LCA studies. Predictive scenarios and scenario ranges were identified as two viable approaches to prospective inventory modelling of both foreground and background systems. To this end, different data sources exist and can be used for the prospective modelling of the foreground system: scientific articles; patents; expert interviews; unpublished experimental data; and process modelling. However, the recommendation of the author is to avoid temporal mismatches between foreground and background systems, suggest that foreground and background system impacts must be reported separately in order to increase the usefulness of the results in other prospective studies.

In another study on prospective LCA, Hummen and Kastner, 2014[139], examined different methods for the assessment of immature technologies, finding that most of these methods revealed a general weaknesses in data quality. In their view, data based on expert estimations impair the validity of results, but are often the only collectable data. In light of this the author stressed that, the biggest effort to conduct an LCA at an early stage is great due to highly intensive data collection and the subsequent requirement for the harmonization of data.

In their assessment, economies of scale yield the best forecasting results, but they recognized that economies of scale are not always applicable. However, Hummen and Kastner emphasized that even simple qualitative assessments can help to integrate the LCA thinking into the iterative development process and to acquire hot-spot knowledge of the environmental impact at an early stage.

In 2020, Mendoza Beltran et al.[140], published a work on prospective assessment methodology, using as case study electric vehicles and internal combustion vehicles. In this work, the authors underlined that prospective life cycle assessment needs to deal with the large epistemological uncertainty about the future to support more robust future environmental impact assessments of technologies. Their approach focused on the use of scenarios, reflecting possible changes in the electricity sector, to integrate the assessment. Specifically, their goal was to integrate the scenario analysis in the study in such a way that the latter systematically changed the background processes in the system boundaries. According to findings of their work, the approach demonstrated that the relative environmental performance of electric vehicles and internal combustion vehicles over time is more complex and multifaceted than previously assumed. Notably, the uncertainty due to future developments manifested in different impacts depending on the product, the impact category, and the scenario and year considered. The author recognized that in order to achieve more robust prospective LCAs, particularly for emerging technologies, the approach could be expanded to other economic sectors beyond electricity background changes and mobility applications, as well as by including uncertainty and changes in foreground parameters.

A further attempt to perfect the prospective assessment methodology was made by Miller and Keoleian, in 2015[141]. In their work they acknowledged that, despite the many associated challenges, LCA methods must be developed for transformative technologies and that the greatest improvement potential occurs at the early phases of technology development. Following on, they advocated the results of a prospective LCA as the right tools to anticipate potential unintended consequences and develop design pathways that lead to preferential outcomes. Delving into the methodology, the authors identified and categorized ten factors that influence the LCA results of transformative technologies with the aim of providing a formal structure for determining appropriate factors for inclusion within an LCA. A schematic representation of Miller and Keoleian's approach is reported in Figure 2.11 along with the list of factors to include in prospective LCAs.

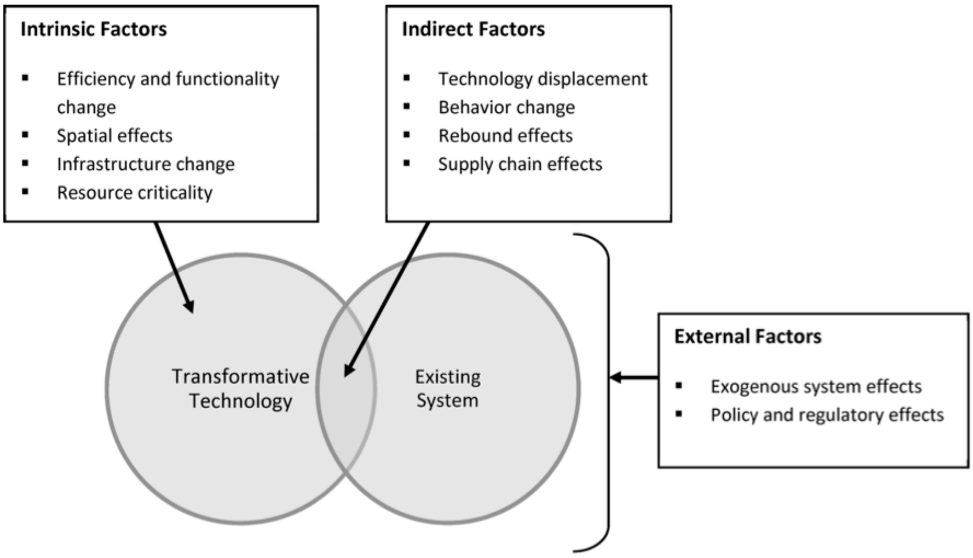
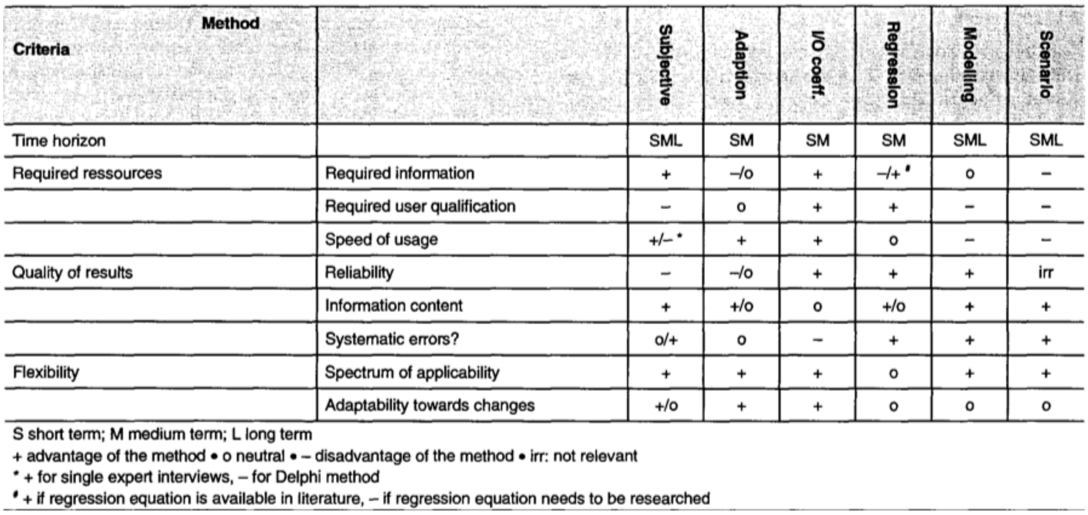


Figure 2.11 - Schematic characterizing ten factors that impact the LCA results of a transformative technology (from Miller and Keoleian, 2015[141]).

According to the results obtained, the authors suggested that the appropriate factors for a prospective analysis should be selected according to the overall research questions of the study and are applicable to both attributional and consequential approaches to LCA. Despite the inherent uncertainty, anticipating the consequences of a transformative technology at an early stage may, in their view, allow for more successful mitigation of future problems. The main outcome from the paper was that in order to make LCA function as a more effective decision support tool and take advantage of the greatest improvement potential, the LCA community needs to address the challenges represented by these technologies and embrace the inherent uncertainty despite the difficulties. The authors finally envisaged that, by creating frameworks to appropriately analyse transformative technologies, it may be possible to make more effective recommendations for early stage design and policy decisions.

2.4.1.2 Dynamic LCA

“The analysis of individual technologies must consider the extremely dynamic development. This concerns the development of products and their production processes as well as their technical performance and the development of background systems”. This is what Pehnt[142] concluded in 2006 after focusing on the prospective assessment of fuel cells use in the energy and transport system. Principally, the investigated forecasting methods are suitable for future energy system assessment. In his work, the author pointed out that the selection of the best forecasting method depends on different factors such as required resources, quality of the results and flexibility. In particular, it is the time horizon of the investigation that determines which forecasting tool may be applied (as reported in Figure 2.12).



Method Criteria		Subjective	Adaption	I/O coeff.	Regression	Modelling	Scenario
Time horizon		SML	SM	SM	SM	SML	SML
Required ressources	Required information	+	–/o	+	–/+ #	o	–
	Required user qualification	–	o	+	+	–	–
	Speed of usage	+/– *	+	+	o	–	–
Quality of results	Reliability	–	–/o	+	+	+	irr
	Information content	+	+/o	o	+/o	+	+
	Systematic errors?	o/+	o	–	+	+	+
Flexibility	Spectrum of applicability	+	+	+	o	+	+
	Adaptability towards changes	+/o	+	+	o	o	o

S short term; M medium term; L long term
+ advantage of the method • o neutral • – disadvantage of the method • irr: not relevant
* + for single expert interviews, – for Delphi method
# + if regression equation is available in literature, – if regression equation needs to be researched

Figure 2.12 - Criteria for selecting forecasting methods in LCA according to Pehnt, 2003[142].

According to Pehnt, environmentally relevant process steps that exhibit a significant time dependency shall always be investigated using different independent forecasting tools to ensure stability of the results. Through this approach, classifiable as dynamic LCA, the author recognized that LCAs, performed at such an early stage of the market development as the one he performed on fuel cells, can only be considered preliminary. In fact, external factors like the rapid technological and energy economic development may translate in further advances for some emerging technologies. Therefore, he highlighted as essential requirement to dynamically accompany the ongoing research and development with iterative LCAs, constantly pointing at environmental hotspots and bottlenecks.

A methodological study on dynamic LCA was published by Alfaro et al.[143] in 2010. The latter focused on including into the assessment those dynamics of parameters that are expected to change over time, and to compare different development pathways. The authors identified that the main limitation of traditional LCAs is the inability to forecast. This keeps it from achieving full acceptance in the context of environmental and industrial analysis. As in the case of other publications on the same topic, traditional LCA was undoubtedly recognized as capable of presenting environmental impacts of established processes, but concurrently unable to do the same for emerging processes or developing products. To that end, Alfaro et al. proposed two different techniques as an addition to the traditional LCA to address emerging technologies: Game Theory and Agent-based Modelling. A schematic representation of the concept behind these two predictive tools is given in Figure 2.13.

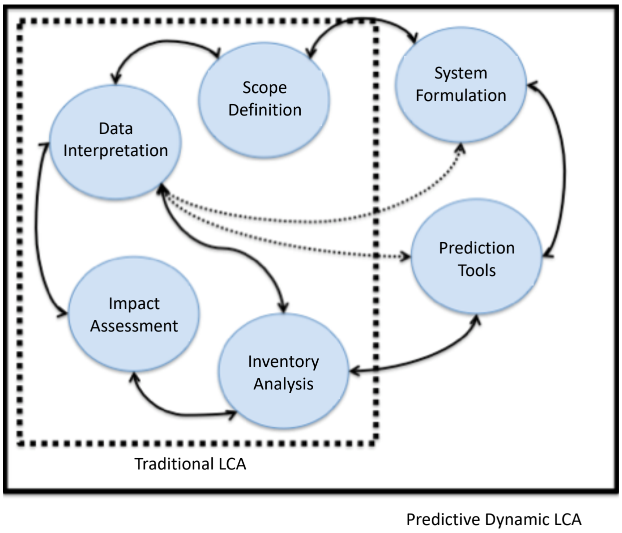


Figure 2.13 - Concept of predictive dynamic LCA and comparison with traditional LCA (according to Alfaro et al.[143]).

The authors insisted that depending on the circumstances, one predictive method could prove more appropriate, whilst, other times, a system could have traits shared by both models and offer no clear method. In any case, in the authors' view, the ideas arising from either model will be fruitful in producing scientifically sound conclusions. On the whole, it resulted clear that predictive dynamic LCAs require a greater effort through increased data gathering as well as selecting and implementing a predictive tool. However, the authors suggested that as more predictive dynamic LCAs are performed, these methods could be refined and become more broadly accepted.

2.4.1.3 Anticipatory LCA

Anticipatory LCA can be defined as "non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology"[4]. This forward-looking (as opposed to retrospective) approach to LCA assessment aims at engaging stakeholders to inform critical modelling decisions and increase credibility and relevance of results.

According to Wender et al., 2014[4], the goal of an anticipatory LCA study is to identify the most relevant uncertainties and engaging research and development decision makers to guide research and development and innovation. In their letter, the authors tried to identify the main flaws of traditional LCA approaches when forecasting the environmental impact of emerging technologies or developing products. To this end, traditional LCAs have a retrospective approach to the assessment of the environmental performances, and hence it is not possible, without a change in the methodology, to calculate the impact of those system that have yet to reach their final form. In Figure 2.14, the concept behind anticipatory (and therefore prospective) assessment is reported as opposed to retrospective LCA.

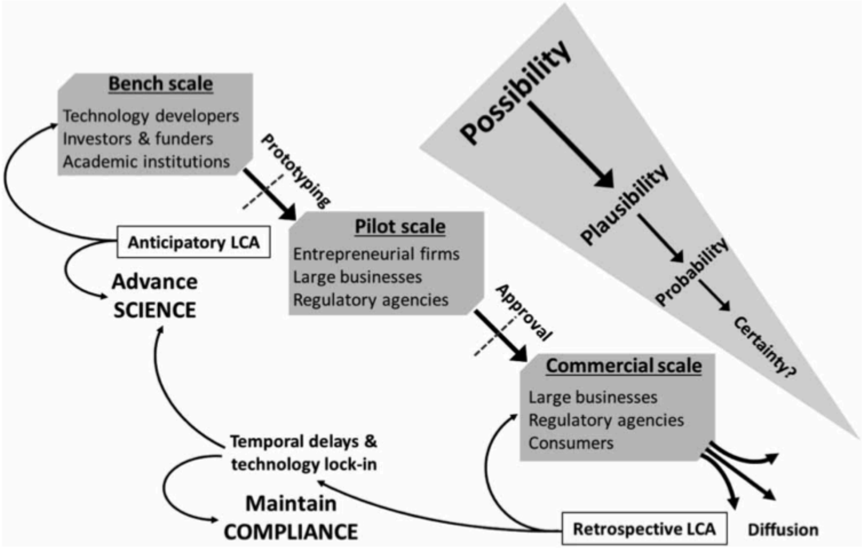


Figure 2.14 - Intervention points of retrospective and anticipatory LCA in technology development (from Wender et al., 2014[4]).

Whilst in the letter no practical indication on the methodology was given, the authors pointed out that the application of such approach would benefit several actors involved in the innovation process, from stakeholders to process developers. On the whole, Wender et al. strongly advocated that the application of LCA earlier in stage-gate innovation overcomes temporal delays and technology lock-in (limiting retrospective LCA), and therefore embed a greater potential to reorient technology development through integration of broader criteria into bench-scale research, resulting in both environmental and economic advantages.

2.4.1.4 Ex-Ante LCA

Ex-ante LCA is an environmental analysis of a technology that is still in its R&D phase. There exist a number of publications in the literature that fit in with this definition.

One of the first papers classifiable as ex-ante study was published in 2011 by Roes and Patel[148]. The authors' approach to the assessment was defined as a prospective, and hence 'ex-ante', study on the production of caprolactam. The authors managed to compare the novel production of caprolactam to conventional ones, and speculate on the results of the environmental impact assessment. Their study was performed in a stage where the novel technologies were not yet fully developed, let alone implemented on a commercial scale. In fact, the data used was theoretically derived or based on lab-scale technology. However, in the paper it is not clear whether the authors included in the LCA a conceptual scale up/out of the technology or not. The lack of sufficient data seemed to be the biggest barrier in this attempt to ex-ante assessment. As happened in most of the studies published on the topic of 'forward-looking' LCA, the authors recommended that in order to reduce the uncertainties, further research is required when the technologies have matured, and better data have become available.

One other work on the topic of ex-ante LCA was published in 2017 by Hesser et al.[144]; a study aimed at integrating environmental considerations during the research and development phase of a novel modification process for a multilayer wood parquet. In this work, the concept of payback period was integrated in the assessment in order to answer the question under which circumstances the modification process pays back from an environmental point of view, and hence guides further R&D activities. Specifically, the LCA was conducted during the research and development phase of the modification process of wood parquet at laboratory scale, and therefore was characterized as ex-ante LCA. The concept of payback period was found to be suitable to comparatively estimate the magnitude of change in potential environmental impacts of product variants. In fact, the authors found out that the extra resource input and the resulting increase in environmental burden of the modification of the multilayer parquet could be justified with the extension of service life length by 10 to 20 %. Hesser et al. stressed that by investigating on multiple payback options, it was possible to frame the change in environmental performance, an essential requirement in order to define the scope of further research and development in a similar target-oriented way.

In another LCA study, Tecchio et al.[128] developed an ex-ante approach for a case study on bio-based polybutylene succinate. In this regard, the driver to using an ex-ante methodology rather than a conventional LCA was that the latter presents some major limitations: it can be performed mainly as an ex-post analysis, and it does not account for the intrinsic properties of the material. As a result of this, productions at the lab/pilot scale cannot be directly compared to industrial systems, primarily due to the large discrepancy in the yields of the processes involved. In order to tackle this issues, the authors focused their efforts on what they thought to be the most relevant added value of the ex-ante methodology, namely the use of primary data collected on lab/pilot scale systems, and they coupled it with data simulated from thermo-chemical considerations. A scale-up protocol was proposed to this end and applied to the case of polybutylene succinate, including a sensitivity analysis in order to take into account the inherent variability of the system.

Tecchio et al. concluded that the life cycle inventory is of paramount importance when performing a forward oriented LCA that includes comparisons with commercial productions. In these cases, in fact, the achievement of fair LCA results requires that the productivity of the systems compared in the analysis is matching. In order to bring the emerging technology under analysis to a scale equal to the reference system, the authors underlined the fundamental importance of having access to direct primary data collected at lab/pilot scale. This allows a coherent modelling of the scale-up of the environmental burden.

A first paper by Villares et al. in 2016 described an approach to the assessment of metal recovery from e-waste defined as cumulative LCA. In this paper the authors reported the results of how the lab-scale metal recovery process was embedded in a larger product system incorporating upstream and downstream processes. It resulted evident that a lab-scale system was not comparable with an industrial-scale system. As the novel process for metal recovery was aimed at future scaling up for industrial use, a second stage of assessment included modelling this by building on the findings of the first stage. In order to do this, a scenario approach was used to determine a plausible commercial-scale system. Then, in a third stage, its environmental performance was compared with a traditional technique for metal recovery (an integrated smelter refinery), in order to further explore its feasibility. A representation of the approach is reported in Figure 2.15.

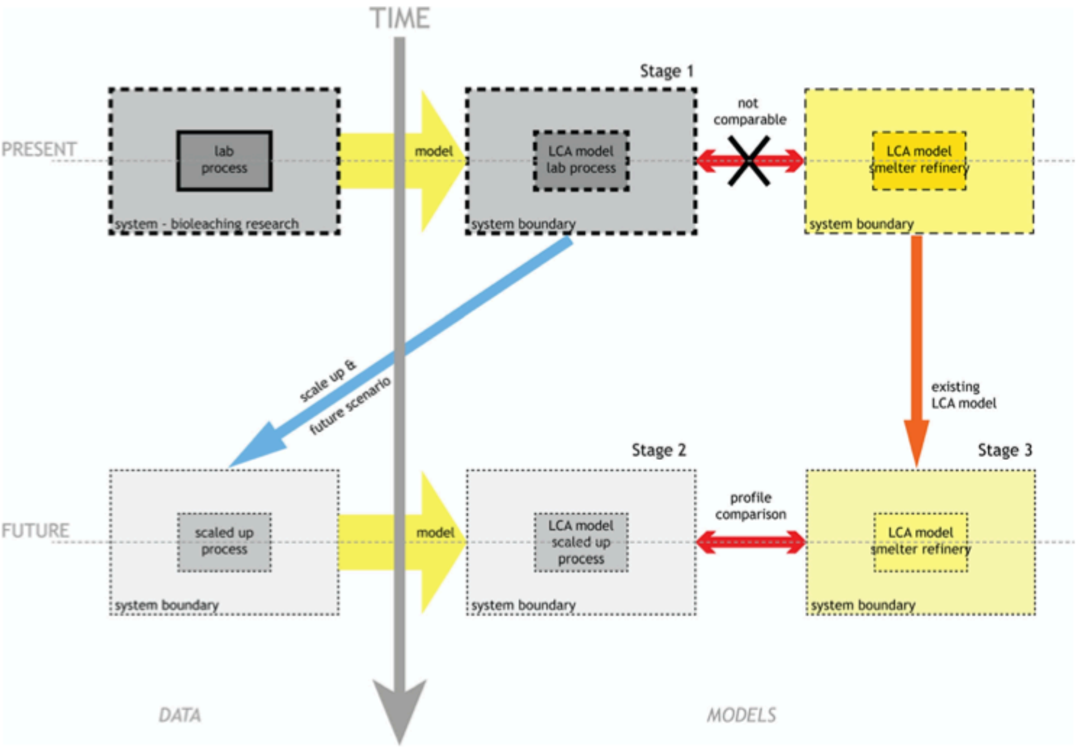


Figure 2.15 - Schematic diagram of the research stages ex-ante LCA and exploratory scenario by Villares et al.[146].

The approach followed some of the guidelines for ex ante LCA recommended by Hospido et al. (2009)[173]. The LCAs adopted by Villares et al. were forward-looking and descriptive, and therefore were defined as ‘prospective attributional LCAs’. Their LCA displayed potential environmental hotspots in the novel metal recovery process, despite uncertainties. The authors were able to demonstrate that the comparison with a full-scale smelter refinery returned an inferior environmental performance.

In a successive publication in 2017[146], Villares et al. analysed their previous LCA on metal recovery from e-waste, with the aim of answering the question: does ex ante application enhance the usefulness of LCA? In this paper, the authors investigated further into the details of the LCA stages used in the previous work, and tried to take out some general recommendation for future ex-ante environmental assessments. Villares et al. acknowledged that the results obtained in their previous paper could not be considered accurate given the early-stage application, yet they served as valuable preliminary information. The uncertainties also prompted further enquiry about the chosen product's system boundary, the role of the emerging technology and the comparability of the technologies. In conclusion, the ex-ante application of life cycle assessment on an emerging technology was found to bring a systematic rigour and discipline to an ambiguous situation at the start of technological development. The authors stressed that applying the LCA framework broadens the scope of the research, introducing a systems approach and long-term view. To this end, environmental aspects and alternative perspectives on the novel technology are also brought into the research domain and the approach creates new knowledge on the novel technology's potential development, and developmental challenges are given definition at an early stage. However, as final recommendation, Villares et al. emphasized that the outcomes of ex-ante LCAs should not be regarded as final results but have a signalling purpose as a contribution to technological development.

2.4.1.5 Consequential LCA

A widely used definition for consequential LCA was provided in the UNEP report on “Global Guidance Principles for Life Cycle Assessment Databases” (UNEP 2011[174]): “to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)”. Examples of consequential LCAs are, for instance, Schmidt's work[175] that aimed at answering the question “What are the consequences of an increased demand of wheat in Denmark?”, or Frischknecht and Stucki's work that investigated on “Which effect does the decision to purchase an additional kWh of electricity have on the electricity market and/or on the environmental impacts?”. According to Guinée et al.[136], consequential LCA shares many of its characteristics with the other ‘forward looking’ LCA methods listed in Table 2.4. As opposed to previous classification, which only distinguished between attributional and consequential LCA, the latter then becomes one mode out of at least six other modes to model lifecycle impacts of possible consequences of changes to existing product systems, or of introducing novel technology or product systems.

According to Kätelhōn et al.[149], consequential LCA provides understanding on "the potential effects of policies on market responses to support environmental decision making". In a study published in 2016, the authors underlined that understanding the environmental consequences of an action, which consequential LCA aims at measuring, is of great importance for policymakers. Kätelhōn et al., however, identified that operational frameworks enabling the modelling of technology choices at an engineering-level detail were lacking in consequential LCA literature. In response to this, they presented in their paper an approach to tackle the mentioned issue through the modelling of technology choices at process-level detail. The approach was called Technology Choice Model (TCM) and consisted in simultaneously determining technology choices in multiple markets, while systematically considering: parameter uncertainties, suboptimal decisions (a company, for example, may decide to use renewable feedstocks along the entire supply chain to demonstrate commitment to environmental protection, even if these feedstocks may be more expensive), and factor constraints (chemical industries, for example, may be constrained in the use of certain chemicals imposing material hearth risks). The aim of TCM was to enable the modelling of both market effects and environmental impacts. The underlying assumption made by the authors was that products are produced by technology mixes rather than single technologies, whereas the shares of individual technologies within these technology mixes are determined by the cost of production, factor constraints, uncertainties, and suboptimal decisions. To demonstrate the validity of such approach, Kätelhōn et al. applied TCM to the case study of rice production.

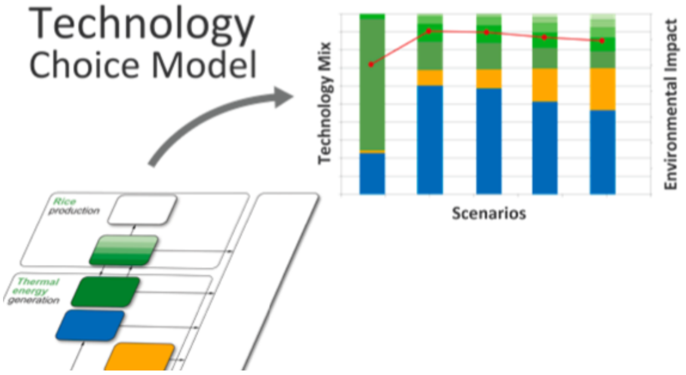


Figure 2.16 - Conceptual representation of Technology Choice Model in the consequential LCA study performed by Kätelhōn et al.[149].

The case study showed that considering uncertainty is not only essential for understanding the quality of consequential LCA results but may also lead to substantially different results. However, the authors underlined that there exists a significant limitation. In fact, operationalizing TCM at a large scale would require a large amount of additional information that was not (and yet is not) available in existing and established process life cycle inventory databases. The feasibility of the proposed approach seems therefore contingent on integrating robustly these databases through the development of meta-data protocols and deeper data collection.

2.4.1.6 Lifecycle sustainability analysis

Life cycle sustainability analysis (LCSA) proposes a transdisciplinary framework of methods and in principle broadens the assessment to include social and economic impacts, and therefore include more than just technological relations e.g. by scaling up the technology to society wide implementation. This may imply generating future scenarios, but not necessarily looking into innovative technologies. In 2008, Klöpffer[36] suggested the formula LCSA=(LCA+LCC+SLCA) as a way to cover the three dimensions of sustainability in the life cycle sustainability assessment for products. To give a guide on how to carry out a LCS Assessment through the combined application of the existing environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA), the UNEP/SETAC Life Cycle Initiative published a LCS Assessment framework[176]. This framework builds upon the ISO 14040 life cycle assessment framework for environmental LCA, comprising four phases: (1) LCSA goal and scope, (2) LCSA inventory, (3) impact assessment and phase (4) LCSA interpretation. Two case studies: Traverso and Finkbeiner (2009)[177] on marble slabs, and Lu (2009)[178] on e-waste management were given to illustrate the practical steps of LCS Assessment.

With regards to LCC, this methodology predates LCA; distinct and different conceptual foundations and methodological approaches can be traced to its developmental roots in systems engineering (Blanchard 1978[179]). According to Korpi et Ala-Risku (2008)[180], LCC was originally designed for procurement purposes in the US Department of Defence (White and Ostwald, 1976[181]) and is still used most commonly in the military sector as well as in the construction industry[182]. There has been limited integration of these methods, although the value of LCC for sustainability assessments has been recognized[183–185]. The adoption of life cycle thinking has been very slow in some industries[186], whilst the public sector has been a relevant promoter for life cycle cost calculations[182].

In 2011 SETAC published a code of practice for environmental life-cycle costing, which provides a framework for evaluating decisions with consistent, but flexible systems boundaries as a component of product sustainability assessments[187]. The code of practice provides guidance that builds on the four-phase structure of the ISO 14040 standard to facilitate definition and application of consistent system boundaries for complementary LCC and LCA studies of a given product system. Goal and scope definition are defined in a similar way to that of an LCA; however, according to the Swarr et al.[187], different parts of the product system can fall below relevant cut-off criteria for the separate LCC and LCA components. One of the examples used in the code is the cost associated with early research and development. This phase may impose significant costs but little environmental impact. To this end, the authors remarked the paramount importance of having both studies refer to a consistent definition of the product system, and that cut-off criteria do not conflict with the intended goal and scope of the study. One challenging aspect of LCC is in fact that the latter attempts to capture all costs across the life cycle, and some costs are borne by different actors with very different perspectives of the costs and potentially conflicting goals. Swarr et al. underlined that although an LCC is conducted to inform decision making of a particular actor, ideally the data can be presented in a way to fairly inform all actors in the product system.

The main driver for LCC studies is to fully take into account the financial costs of life-cycle environmental aspects and impacts that result from a decision. As proposed by Hunkeler et al.[120] and further discussed by Ciroth et al.[188] this can be achieved through the internalization of the costs, i.e. by applying the polluter pays principle - those who produce pollution should bear the costs of managing it to prevent damage to human health or the environment - or by using information to make the impacts visible at the time of the decision.

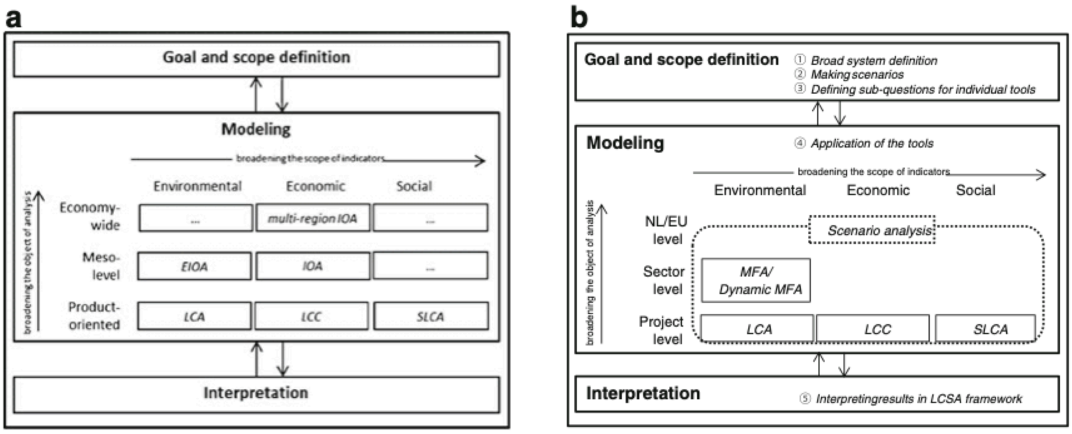
With regard to the inventory analysis, LCC shares with LCA the same data availability and quality issues. In addition, as virtually everyone is familiar with currency units, costs data can create a false sense of certainty[188]. Many challenges there exist in fact when compiling a coherent inventory for LCC studies. Firstly, cost data is often more volatile than physical units, and hence the practitioner needs to put extreme attention in keeping the cost data up to date and ensure consistency across the inventory. A problematic associated with the latter aspect is that costs data may be gathered in different currencies and reflect different time periods. Therefore, the inventory data need to be presented in a common currency using appropriate exchange and discount rates. Secondly, the cost data will likely come from different sources, thus rendering a difficult task putting together a consistent data set for a study. Furthermore, some data may be business sensitive. Different industry sectors have customized cost models and terminology that may have to be reconciled in constructing the inventory[187].

Conversely to what happens during the discussion of the results of LCA studies, there is no comparable impact assessment phase in LCC since all inventory data have a single unit of measure that is the selected currency. Cost data are a direct measure of the economic impact of a system. On the other hand, the procedures for interpretation, communication, and review are a common factor with LCA.

With specific regard to the integration of LCC in the LCSA, Guinée et al., 2011[84], underlined that establishing a framework for LCSA does not make product-oriented LCA and LCC superfluous, but on the contrary, it only relates product-oriented LCA and LCC to specific questions, for which these specific methods are suitable. According to the authors, one of the main challenges faced is to structure and make available in a practical way the plethora of

LCA and disciplinary models to various types of life cycle sustainability questions. In other words, making the LCSA framework operational for LCA practitioners, substantial research is needed. A map of such research was published in 2005 by Foran et al.[189]. The general scientific challenge resulting from this map was to derive consistent criteria for implementing methods in relation to specific lifecycle-based questions. To this end, the authors highlighted that a vast amount of research was still needed to achieve this, with specific regards to the choice of attributional, consequential, and scenario-based modelling of systems and related timeframes, including aspects of unpredictability of emerging systems, complex adaptive systems, and other contingencies. Furthermore, a new generation of ISO-type guidelines and LCSA handbooks were thought to be primary valuable for consistently linking environmental, economic, and social disciplinary models to specific questions.

In 2013, Hu et al.[150] published a LCSA on the case study of concrete recycling. In the paper the authors reported a very thorough review of the LCSA methodology. In their view, the methodology was still lacking rigour in the procedure for its application. Even though the LCSA was developed within the CALCAS project (Coordination Action for innovation in Life Cycle Analysis for Sustainability, was a pan-European project, financed by the Sixth Framework Programme of the European Commission; main goal was the review of the basic current paradigms of LCA in order to overcome its current limits) the method was in fact far from being standardized. To this end, the author tried to put the LCSA framework into practice on the case study of concrete recycling, and came out with five operational steps needed in their view to implement the LCSA framework (as shown in Figure 2.17): (1) broad system definition, (2) making scenarios, (3) defining sub-questions for individual tools, (4) application of the tools and (5) interpreting the results in an LCSA framework.



Framework for LCSA from Guinee et al. 2011

Operational steps for LCSA in C2CA

*C2CA was a project funded by E, focused on innovative technologies and eco-design recommendations for reuse and recycling of Construction and Demolition (C&D) waste

Figure 2.17 - Framework, methods and steps of life cycle sustainability analysis according to Hu et al. (b) and Guinée et al (a).

Steps 4 and 5 were elaborated only theoretically in Hu et al.'s paper. The case study showed that the operational steps were especially useful at the stage of defining the goal and scope, specifically for defining the sub-questions suitable to be assessed by the individual analytical tools (LCA, LCC, SLCA, etc.). Finally, the author acknowledged that despite having provided through their study useful steps for the operationalisation of the LCSA concept, additional case studies were needed to move LCSA into a practical framework for the analysis of complex sustainability problems.

To this end, Van Der Giesen et al., (2013)[151] followed up on the conclusions of Hu et al., stating that practical experience with LCSA was very limited. In their paper, Van der Giesen et al. reported an attempt to put the LCSA framework into practice by assessing the sustainability of solar fuels. The starting point of their project was the hypothesis that new technologies can only be practically implemented if they fit into a socially, economically and ecologically sustainable context. Building upon this hypothesis, the analysis should therefore aim, in the authors' view, at identifying performance criteria which a new technology needs to fulfil in order to compete in the existing market. In the paper it was argued that a LCSA study should be initiated with a broad but relevant system description as the first of in total five steps, in accordance with Hu et al.[150] and Guinée et al.[84]. To this end, the authors focused only on the first – system description, identifying and describing the technology, its intended application, which share of specific demand for service will be met, which other technologies contribute in meeting this demand, the relevant indicators for addressing sustainable impacts of meeting the demand, and developments over time. However, the subsequent four steps of the LCSA framework were not completed, leaving open questions on the possibility of practical applying the full methodology.

2.5 CONCLUSIONS

The literature review has highlighted past and current trends in the application of LCA methodology, and offered a glimpse at the possible evolution of the methodology in the next future. It is striking how the LCA methodology has incorporated over time diverse inputs from the ever-changing demand of the society and how, in reflection to this, practitioners have set increasingly more ambitious goals as outputs of the assessment. The methodology is developing in a direction where factors from the economic and social spheres are integrated into the assessment of life cycle of a technology. Compared to standard LCA, multi-criteria evaluation is believed to offer a more robust understanding of the technology under analysis, therefore helping both scientists in the process development and stakeholders in the deployment.

However, an underlying dilemma has emerged predominantly in the last decade: the usefulness of LCA is confined to a small segment of the decision-making process that occurs after the technology has been deployed at large scale. This way of performing the assessment, namely retrospective or ex-post assessment, is incapable of aiding the development process, guiding it and hence avoiding a set of wrong decisions that arise from not having the complete picture while the technology is being developed. This is to say that a consistent portion of the environmental, economic and social impact that a technology or a product have at large scale stems from decisions taken during the early stages of the process development. These decisions are taken on the basis of the knowledge that is available at each stage. However, the latter may result incomplete as there is no such standardized and accepted methodology that integrates environmental considerations as part of the process development strategies.

In response to this shortcoming, new approaches to LCA have been and are currently being developed in order to shift from ex-post assessment to ex-ante or forward looking assessment, and hence provide knowledge on environmental and social impacts, and on the economics of the technology that is needed before the latter enters the market. By following these premises, it will be possible to anticipate the future impact and intervene in the process development and correct the trajectory in time.

However, the literature review has identified several challenges in the definition of such approaches and a considerable paucity in the practical applications of such methodologies. To this end, the major challenges are:

- Robustness of the life cycle inventory

  The life cycle inventory step is of paramount importance when forecasting the environmental impacts and cost of a technology that is yet to be deployed. Significant uncertainty can be generated in this phase of the LCA; thus, it is required that sufficient data and knowledge on the novel technology is available in order to minimize errors downstream in the LCIA phase. This means that not every system can be subjected to LCA at early stages. To this end, from the literature review it emerges that a big gap exists in the assessment of emerging technologies at lab/pilot scale. The underlying problem is the necessity of having inventorial information on the large-scale setup, which clearly is not available in the nascent phases of the process development. In fact, the biggest barrier resulting from the literature review is that of the scale, which brings a large grade of uncertainty. Notwithstanding this, most of the ‘forward looking’ LCAs found in the literature focus more on post LCI analyses that quantify the uncertainties generated from the LCI, rather than focusing on the LCI itself and defining an analytical approach to LCI of emerging technology that allows to: cut down uncertainties, obtain robust LCI and hence credible LCA results. Rare are the cases in which this happens, for instance trying to integrate available inventory data on lab setups with scale-up/out considerations and even more rare are the assessments that take into account a pilot scale setup (TRL 4-5).

- Need of multi-criteria assessment

  It is evident that, in the last decade, a transition has started from LCA oriented solely on the environmental performances to multicriteria evaluation taking into account different aspect of a technology. Economics and social impacts are increasingly part of the LCA. The definition of a unified and standardised methodology is still far. Whilst the economic analysis seems possible, the application of social values into the assessment is at an early stage. Big gaps exist in the quantification and weighing of social impacts in the various and multi-diverse aspect of it.
- Lack of practical examples and comparative analyses

  There is lack of practical examples of LCA of emerging technologies in the literature. Limited are the assessments available for the environmental performance delivered by the application novel production routes in place of conventionally adopted systems. Specifically, the field of process intensification (PI) offers a great number of promising technologies that call for all-round assessments able to determine in an anticipatory fashion their future environmental and economic performance. To this end, the environmental impacts of novel technologies need to be benchmarked with the state-of-the-art technologies.

Building upon the finding of the literature review, the next Chapter of the Thesis will report the description of the methodology adopted as well as an introduction to the four case studies subjected to assessment.

3 APPLIED FRAMEWORK AND INTRODUCTION TO THE CASE STUDIES

Part of the content of this Chapter was published in:

- Journal of Cleaner Production
  Grimaldi, F. Pucciarelli, M., Gavriilidis, A., Dobson, P., Lettieri, P., 2020. Anticipatory Life Cycle Assessment of Gold Nanoparticles Production: Comparison of Milli-Continuous Flow and Batch Synthesis
- Journal of Industrial Ecology
  Grimaldi, F. Ramirez, H., Lutz, C., Lettieri, P., 2020. Intensified Production of Zeolite A: Anticipatory Life Cycle Assessment of a Continuous Flow Pilot Plant and Comparison with a Conventional Batch Plant (Currently under review)
- Journal of Advanced Manufacturing and Processing
  Grimaldi, F., Leon Izeppi, G., Kirschneck, D., Lettieri, P., Escribà-Gelonch, M., Hessel, V., 2020. Life cycle assessment and cost evaluation of emerging technologies at early stages: The case of continuous flow synthesis of Rufinamide

3.1 CHAPTER SUMMARY

In the previous chapter, the Life Cycle Assessment methodology has been described and critically reviewed. The literature review has offered a temporal analysis of the LCA methodology over time, defining the past and current trends of its applications. A critical review of the previous attempts to the assessment of novel technologies has brought to light current research gaps and helped identifying pending challenges.

Building upon these findings, this chapter introduces the framework for the assessment of emerging technologies, that aims at integrating the existing LCA methodology with additional assessment steps and considerations to overcome the gaps emerged in the literature review. The methodological approach is described, and four case studies - four emerging technologies selected from academic and industrial R&D - are presented.

3.2 THE FRAMEWORK

3.2.1 GOAL AND SCOPE DEFINITION

Methodological choices in any form of assessment or research are determined by the goal of the study and the research questions asked. In order to understand the merit of any assessment, choices and research questions should be clearly defined. The ISO standard prescribes to define the goal and scope of the study as a first step[190].

The primary premise for LCA on emerging technology is that the latter is developed to set a new state of the art for the target production system and render the current industrial practice more efficient by implementing the technology in the technology mix; the new technologies will likely replace or complement well-established mature technologies. It is therefore a requirement to include a comparison with these incumbent technologies as part of the assessment. The inherent objective of the LCA on emerging technologies is in fact to benchmark the future environmental performance of the new technology against one or multiple conventional technologies, in order to gain insights into the further developments of these not-yet-introduced technologies and guide upcoming efforts in research and development of the new technology.

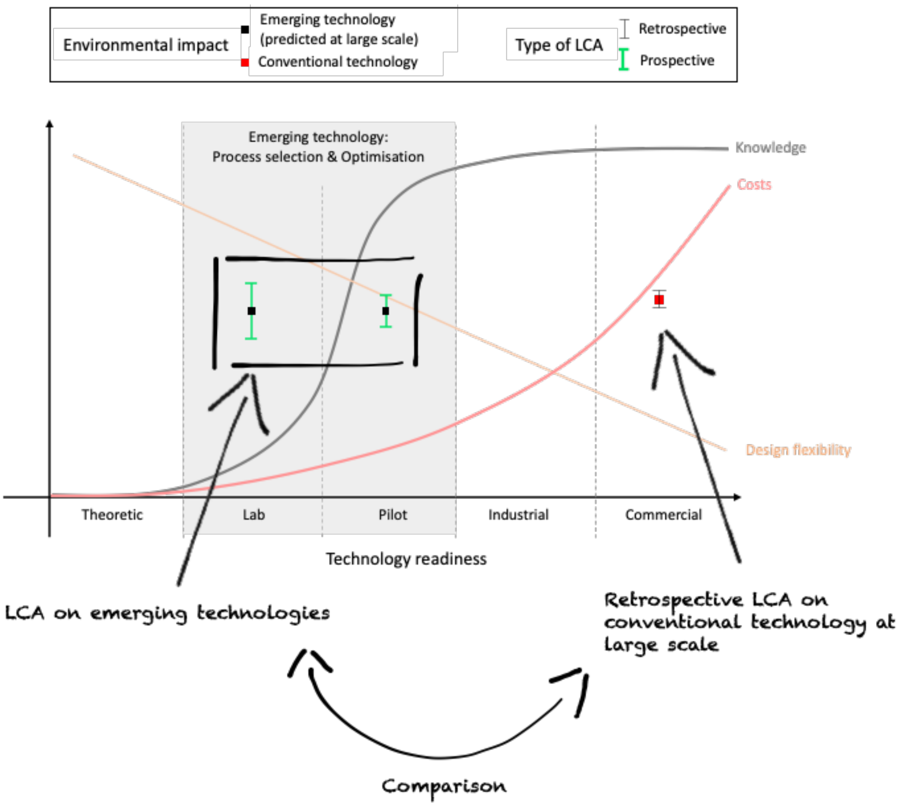


Figure 3.1 - Output of prospective LCA during technology development and comparison with retrospective LCA on conventional technology at large scale.

The main audience for this type of studies are hence technology developers and policy makers. In order to produce a balanced comparison of technologies, a consistent modelling framework for all lifecycle phases and boundaries conditions is needed. Furthermore, both conventional and emerging technologies are assessed under the same temporal and geographic scope, functional unit and impact categories; this is the sine-qua-non condition for a coherent comparative analysis. Specifically, critical points in LCA of emerging technology include:

- Temporal and geographical scope

  A first inherent requirement for assessing technologies before market implementation is to define when and where the new technology will be introduced in the market. Identifying the temporal and geographical collocation of the new production system, once the latter is deployed, is of fundamental importance in order to balance the comparison with the existing conventional technology mix. As a result, this has direct effect both on the LCA modelling of emerging and conventional system, and on the calculation of the impacts for both systems. In fact, with regards to the LCA model, the temporal and geographical collocation determine the processes that compose the background system: highly influential factors are affected by this choice such as, for instance, the electricity mix to be used (this varies depending on the country and year). Furthermore, the choice of "where" and "when" defines the magnitude of the target productivity of both emerging and conventional production systems. The cumulative productivity of a certain product is region-specific, and hence it has influence on the target productivity of the system under analysis. This affects the calculation of the results during the normalisation analysis and the interpretation phase, as the weight and background of the selected product depends on the temporal and geographical collocation.

- Functional unit

  The functional unit is defined necessarily in the same way for both the emerging technology under analysis and the reference conventional system. In other words, this has to be the same for both systems in order to avoid bias in the calculation of the environmental impacts. It is in fact only possible to compare and benchmark two competitive systems, if these provide the exact same product (or service). An example of such challenge is reported in Van Der Giesen et al. (2014)[151], in which a total of four functions were defined for solar fuels produced from CO_2. In that study it is clearly shown that an unambiguous function (or reason) to produce solar fuels is hard to define. Hence, the choice for the functional unit, in the case of LCA of emerging technologies, needs a more careful deliberation than is common practice in classical retrospective LCA. For example, the functional unit selected in the first of the four case studies presented in this Thesis is “1 litre of gold nanoparticles product (of Optical Density 1, and mean diameter of 10 nm), produced from a plant with a productivity of 45 m^3 of product per year”.

- Choice of impact categories

  As stated previously, LCA on emerging technologies aims at analysing if the novel system can have (in projection) environmental and economic advantages over the conventional technology. To this end, the selection of the impact categories is the same for both systems, and also it should not be narrowed down excessively in order to avoid excluding unexpected impacts. Namely, the first approach is to consider a broad set of impact categories, in order to embrace all the potential impacts arising from the emerging technology, and leave none of them unconsidered. Successively, in the next steps of the LCIA, it is hence possible to focus on the impact categories that resulted as primary concerning and hence narrow the scope of the analysis on these.

The structure of the applied framework for the assessment of emerging technologies is represented in Figure 3.2.

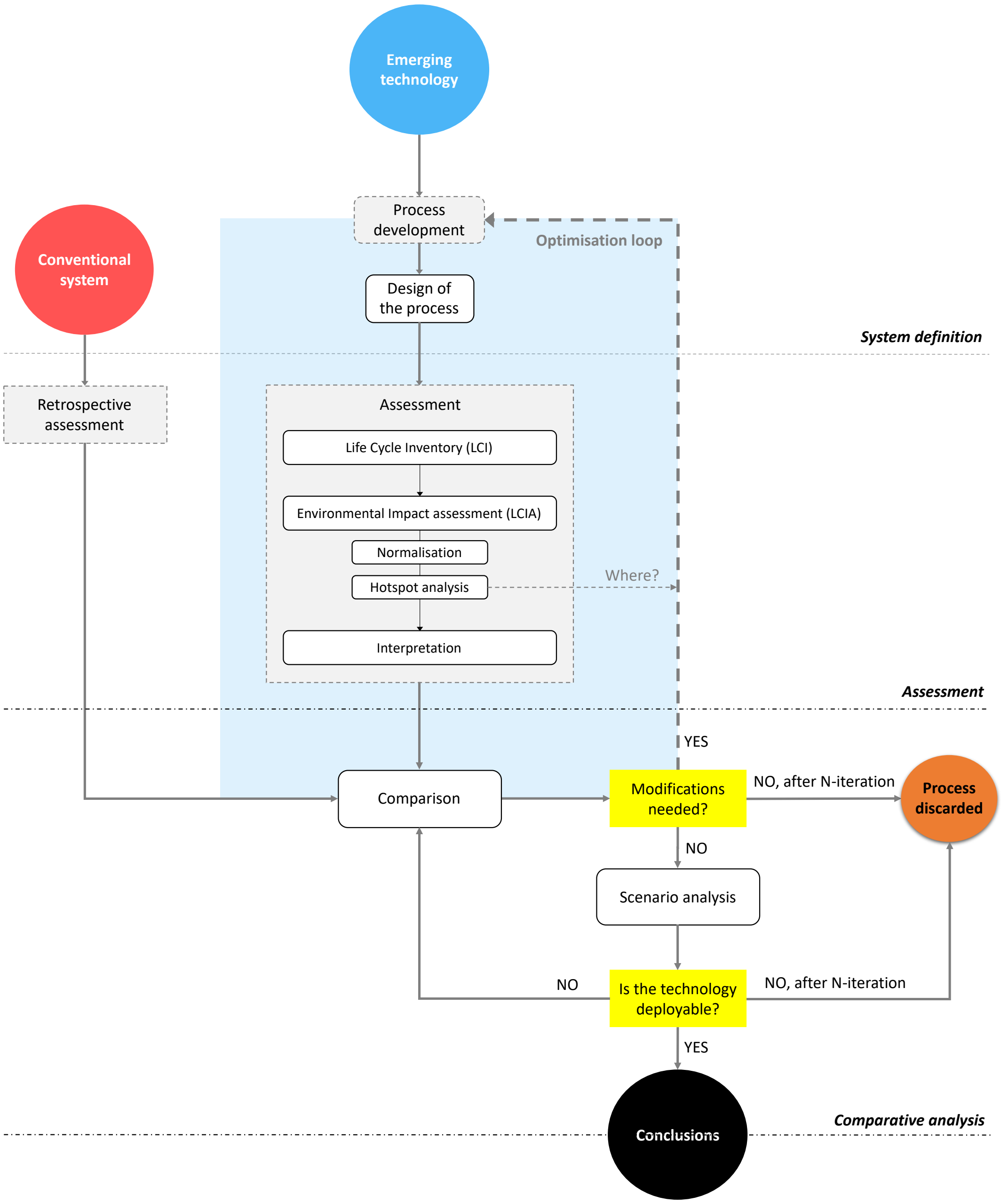


Figure 3.2 - Framework for technology comparison at early stages of the process development.

The proposed framework operationalises the LCA as a tool for: (1) integrating the technology development with environmental and economic inputs, in order to maximise environmental and economic performances of the emerging technology under analysis; (2) helping the decision making process on the deployment of the emerging technology, by benchmarking the projected performances of the latter against conventional production systems at commercial scale.

In order to enable these two functions, the conventional production system is assessed in a retrospective fashion, i.e. following the procedure of a conventional LCA, by assessing the commercial scale system that is already available in the market; the output of the assessment are then used as reference lines on which the environmental and economic performances of the emerging technology are evaluated.

On the other end, the emerging technology is assessed in a prospective fashion (see Figure 3.1). The novel production system under analysis is firstly brought conceptually from lab/pilot scale to the same scale as the reference conventional system. Subsequently, the scaled-up/out system is subjected to assessment. Normalisation and hotspot, and uncertainty analysis are performed in this phase in order to generate the highest level of detail. The output of the assessment is then compared with the result of the LCA on the conventional system. As mentioned before, one of the inherent objectives of the LCA on emerging technologies is in fact to benchmark the future environmental performance of the new technology against one or multiple conventional technologies, in order to gain insights into the further developments of these not-yet-introduced technologies and guide upcoming efforts in research and development of the new technology.

To this end, the results of the comparison are used as inputs to the process development. The information generated from the comparative analysis comprises quantitative and qualitative information of environmental and economic performances of the emerging technology with respect to the conventional system. Furthermore, by means of the hotspots and normalisation analysis, the inputs carry information on the possible intervention points in the technology development: both in terms of life-cycle phases (e.g. transport, production phase, waste treatment) and in terms of specific activities taking part to the life cycle of the production system (e.g. preparation of precursor, pumping, hazardous waste incineration, etc.). The underlying concept is to enable an “optimisation loop” with process information and projected environmental and economic impacts travelling back and forth between process development and assessment phase; thus, contributing to maximising the environmental and economic performances of the emerging technology before the latter enters the market.

A scenario analysis is also performed to capture either the hypothetical impact of replacing conventional systems with the emerging technology, or the conditions (e.g. yield of a step of the synthesis, efficiency of the recirculation system, etc.) under which the latter would bring advantages over conventional systems and, and hence be deployed.

In summary, the framework can be subdivided into three main phases: system definition, assessment, comparative analysis. In the next sections these phases will be analysed in detail, touching on the methodological recommendations as well as on the procedures followed for the calculation of quantitative data.

3.2.2 SYSTEM DEFINITION

In this phase - system definition - the process flow diagrams (PFD) are defined for both the emerging and conventional technologies. With regards to the latter, the construction of the PFD originates from a lab scale and is brought, through a scale up/out study, up to a commercial scale matching the reference productivity. Material and energy flows data are either collected (on-site collection where it was possible) or calculated. In fact, in this phase, direct data are integrated (where the information is missing) with indirect data calculated on the basis of process knowledge obtained in the experimental phase. This is to say, for instance, the sizing of a full-scale heating system, or pump feeding, is derived from the experimental setup and scaled up conceptually, keeping unvaried the heat and mass transfer characteristic of the original setup. A practical example is reported in section 5.3.2, with regards to the system definition of the case study II – Gold nanoparticles production for biomedical applications.

As previously anticipated in the description of the framework (see section 3.2.1), LCA and cost analysis serve the purpose here of optimizing the projected full-scale PFD of the emerging technology through a loop-system, by performing an assessment of the interim system and providing feedbacks on the inputs used in the PFD definition. These inputs - coming from the first iteration of assessment - enable the optimisation of the novel production system. The modified system is then re-assessed and used as basis for the successive iterations. After a sufficient number of iterations, the iterative loop is ended, and the results of the assessment are further benchmarked in the comparative analysis step. The goal of the explained approach is to take the system to its optimum point in terms of costs and environmental impact, keeping the product quality unvaried. The full set of operations involved in a full-scale PFD is taken into account, namely, the precursors preparation, pumping, synthesis, heating and mixing, cleaning, separation, waste disposal, etc.

3.2.3 ASSESSMENT PHASE

The assessment phase is composed of three main steps: Life cycle inventory (LCI), environmental impact assessment and cost assessment.

3.2.3.1 Life Cycle Inventory

This is an inventory analysis in which all the relevant inputs and outputs of the product system are quantified (as indicated by the ISO 14040[190]). This step serves the purpose of qualifying and quantifying material and energy streams throughout the life cycle of the production and is the basis from which the environmental impacts and costs are calculated.

At the basis of the inventory analysis there is the definition of the Functional Unit (FU), that quantifies the function of the product under study and serves the purpose of providing a reference to which input and output data are normalized. Specifically, the functional unit is defined necessarily in the same way for both the emerging technology under analysis and the reference conventional system. In other words, the FU has to be the same for both system in order to avoid bias in the calculation of the environmental impacts. The data for the LCI are quantified for each unit process included into the system boundaries defined (Figure 3.3). System boundaries are subdivided into two macro systems: foreground and background systems.

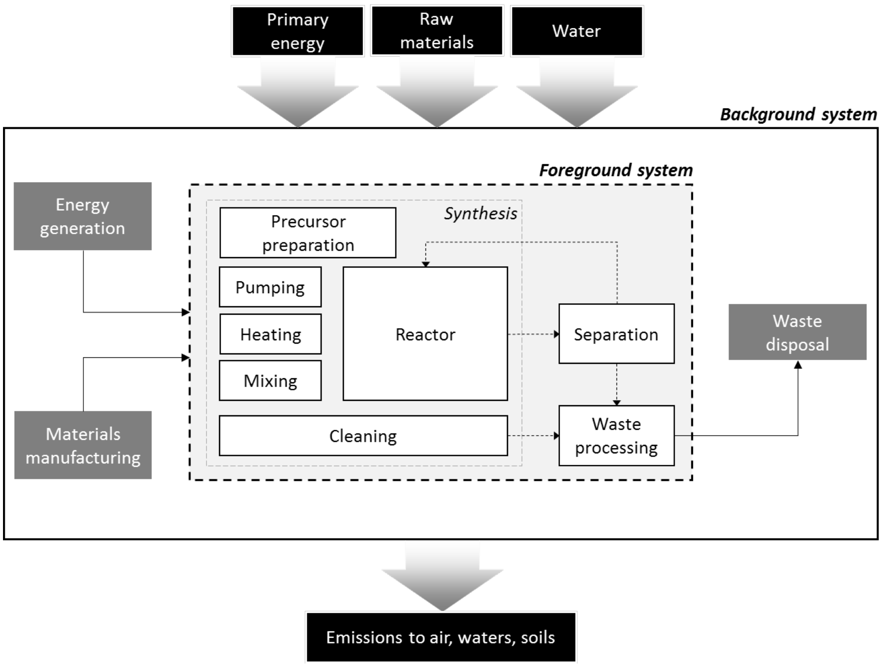


Figure 3.3 - System boundaries: foreground and background systems.

The foreground system is composed of the array of operations occurring in the production phase, separation, cleaning and waste processing. Foreground data are collected to describe and model the new technology as well as the conventional. Background data are required to represent the context of the study, usually consisting of data for upstream supply chains necessary for the emerging and incumbent technologies to perform the selected functions.

Unavailability of life cycle inventory data are a common hurdle encountered in LCA of emerging technology; as explained in section 3.2.2, this is overcome by making use of secondary data in combination with a uncertainty analysis.

With regards to foreground data, these are usually not fully available for new technologies. The available data and knowledge are case-specific, and therefore it is recommended to perform the assessment only on those technologies that are in a TRL phase (technology readiness level) of 4-5 (bench scale-pilot scale). The data that are available most likely originate in lab experiments or pilot projects and are therefore not fully representative of operational scales. This is why the proposed framework includes a thorough description of the novel system under analysis, along with all the assumptions made to derive the full-scale PFD, and uncertainty and scenario analysis to take into account the intrinsic variability of the emerging technology.

On the other hand, data representing commercial scale operation are usually available for the incumbent technology given the more advanced level of development. To this end, the available data for both systems do not automatically allow, in most cases, comparable systems boundaries. This requires a hypothetical expansion of the system boundaries of the novel systems as described in section 3.2.2, to cover all the missing activities that are present in the life cycle of the conventional production system, but not yet defined for the emerging technology (e.g waste treatment).

With regards to the background system, this comprises the set of operations and services that revolve around the synthesis, and whose impacts were taken into account in the assessment: electricity production, raw materials extraction, chemical production and waste disposal. This is highly relevant, since background processes usually make up to 99% of all unit processes in a product system and only occasionally fall below 95%[191]. This means that the impacts caused by background processes are of considerable influence on the outcomes of an LCA study. Several authors have stressed that a temporal mismatch between background and foreground systems is to be avoided[192–194], which can only be facilitated by a clear definition of the temporal scope in the goal and scope definition phase of the study, as explained before. Each process is built into the model by compiling the material and energy balance occurring in them through the standardised approach indicated in the ISO 14040[190] and these include:

- Energy inputs, raw materials, ancillary inputs, other physical inputs,
- Products, co-products and waste,
- Emissions to air, discharges to water and soil, and other environmental aspects.

Finally, it is important to stress that the functional unit and the system boundaries defined in these first steps of the assessment, are the same for both emerging and conventional production system: this is a *sine qua non* condition for achieving a coherent comparison.

3.2.3.2 Environmental impact assessment

The environmental impacts of the batch and continuous flow production systems are calculated. This step is called Life Cycle Impact Assessment (LCIA) and aims at translating the elementary flows described in the life cycle inventory into environmental impacts. It assigns to each flow (i.e. emissions or resource use of a product system) an impact on the environment. This is achieved by means of impact categories: an impact category covers a specific aspect of the environmental consequences of the emissions arising from the production system. The environmental impacts are expressed on the basis of the chosen FU.

As previously described in section 2.2.5.4, an environmental impact can be defined as a set of environmental changes due to causes originating in human activities. LCIA characterisation methods essentially model the environmental mechanism that underlies each of the impact categories as a cause-effect chain starting from the environmental intervention (emission or physical interaction) all the way to its impact. To this end, the impact can be expressed throughout midpoint and endpoint methods, depending on the type of output the analysis is meant to provide (i.e. increased chemical concentration in a lake vs extinction of species). As a general rule, the further the outcome of the assessment is expressed in the cause-effect chain, the more the results can be biased. In this Thesis, the chosen LCIA method implies a midpoint level assessment in order to minimize errors.

When applying LCA on emerging technologies studies it is important to consider the eventuality that potential environmental impacts of new technologies could not automatically be covered by the existing impact categories commonly used in retrospective LCA studies. Recent LCA studies of new technologies and new materials stress the limitation of the lack of characterization factors at the LCIA phase of LCA studies[4,195–197]. A good example of this is the upcoming interest in nanotechnology. It has been recognized that properties of nanotechnology are not yet well known and that considerate efforts should be put in developing methods to assess the impacts on the environment[198]. With regard to nanotechnology, for instance, there exists still a paucity of toxicological data, as none or not enough ex-vivo and in-vivo tests have been conducted. Therefore, in this specific case it is not possible to factor into the assessment the use phase of nanomaterials because this would bring a great level of uncertainty. To this end, in these cases, it is recommended to follow a cradle-to-gate approach, confining the analysis up to the production phase, in order to avoid biases in the calculation of the environmental impacts. However, it is worth noting that in a comparative study, the end product is the same for both emerging and conventional technologies. Therefore, it is still possible to determine which production technology has the best environmental performance as the missing information (e.g. toxicology) is a factor in common between the two systems and it is balanced out by the comparative analysis. Furthermore, in order to reduce the unattended impacts, it is paramount to consider as first approach the broadest set of impact categories available in the selected LCIA method. Only in a second round, once the criticality of the environmental impact has been identified in some specific impact categories, it is possible to narrow down the scope of the analysis to specific aspects of the environmental performance.

In this Thesis, ILCD/PEF recommendation 1.09[72] is the chosen method for the LCIA. This method fixes the quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories. The database used for the model is GaBi ts 8.7 (SP36) professional + extensions (II, VI, IX, XVII) and Ecoinvent 3.6 (integrated SP36): the datasets are in compliance with the ISO 14044[71], ISO 14064[199] and ISO 14025[200] standards. In general, environmental impacts are estimated using a cradle-to-gate boundary for European production: in other words, the activities that compose the life cycle (e.g electricity production) are region-specific and are modelled on the basis of European activities. The environmental impacts of the batch and CF systems are expressed for different impact categories; each impact category covers a specific aspect of the environmental consequences associated with the emissions arising from the production system. These impact categories are reported in Table 3.1, alongside with the abbreviations adopted in the discussion of the results for the case studies.

Table 3.1 - Impact categories used for the LCIA and description (from the LCIA method 'ILCD/PEF recommendation 1.09'[72]).

Impact category	Description	Unit	Abbr.
Acidification	It is mainly caused by air emissions of NH_3, NO_2 and SO_x.	[mole H^+ eq.]	A
Climate change, excluding biogenic carbon	Contributions of the greenhouse gases to the global warming and climate change	[kg CO_2 eq.]	CC
Ecotoxicity freshwater midpoint	Toxic effect on aquatic freshwater species in the water ecosystems.	[CTUe]	EcoTOX
Eutrophication freshwater midpoint	Eutrophication effects in the freshwater compartment.	[kg P eq.]	E fw
Eutrophication marine midpoint	Eutrophication effects in the marine compartment.	[kg N eq.]	E mw
Eutrophication terrestrial midpoint	Eutrophication effects in the terrestrial compartment.	[mole N eq.]	E t
Human toxicity midpoint, cancer effects	Toxic effect on humans referring to potential cancer effects.	[CTUh]	HT c
Human toxicity midpoint, non-cancer effects	Toxic effect on humans referring to potential non-cancer effects.	[CTUh]	HT non-c
Ionising radiation	Human exposure to ionizing radiation with potential alterations in the DNA	[kBq U235 eq.]	IR
Ozone depletion	Depletion of the ozone layer at the stratosphere level.	[kg CFC-11 eq.]	OD
Particulate matter	Direct and indirect contribution to particulate matter formation	[kg PM2.5 eq.]	PM
Photochemical ozone formation midpoint	Contributions of VOC (volatile organic compounds) and non-VOC to the formation of ozone at troposphere level.	[kg NMVOC eq.]	POF
Resource depletion, water	Water resource depletion.	[m^3]	RD water
Resource depletion, minerals, fossils and renewables	Depletion of mineral and fossil resources.	[kg Sb eq.]	RD m, f, ren

For sake of readability the results of the impact assessment are presented across the manuscript through the aid of a number of indexes that were used either for calculation or expression of the results. These indexes are:

- Absolute impact ($\mathrm{Impact}_{\mathrm{i,tot}}$)

  It is the environmental impact of the emerging or conventional production system, in a given impact category i.

$$Impact_{i,tot} = \sum_j Impact_{i,j}$$

  where $i = impact\ category$; $j = group\ [Energy\ consumption, chemicals\ \dots]$

- Impact difference ($\Delta Impact_{i,tot}$)

  It is the difference of environmental impact between emerging and conventional production system in a certain impact category.

  $$\Delta Impact_{i,tot} = \sum_j \Delta Impact_{i,j}$$

  It is composed of the sum of the differences of environmental impact between emerging and conventional production system for each inventory group (i.e. Chemicals, Waste disposal, etc.):

  $$\Delta Impact_{i,j} = Impact_{i,j}^{emerging\ tech.} - Impact_{i,j}^{conventional\ tech.}$$

  where $i = impact\ category$; $j = group\ [Energy\ consumption, chemicals\ \ldots]$

- Impact Contribution ($X_{i,j}$)

  It is the share, referred to a given group *j*, of the total impact in the chosen impact category i.

  $$X_{i,j} = \frac{Impact_{i,j}}{Impact_{i,tot}}$$

  It is used to evaluate the contribution of each stage of the synthesis to the overall impact.

The procedure followed in the normalisation analysis is reported below.

- Normalisation

  Through the normalisation, the environmental impacts of the LCIA results are compared to the environmental impacts arising from a defined geographical region or sector, for each impact category. This step also enables the comparison of the environmental impacts across different impact categories. The normalised impact (*NI)* is calculated by multiplying the impact of the product by the normalisation factor (*NF*):

  $$NI_i = Impact_{i,tot} * NF_i \qquad (10)$$

  where, *i* is the considered impact category.

  The chosen normalisation method is ILCD/PEF recommendation 1.09[201]: the normalisation factor is expressed in impact per person equivalents (*P,* representing the reference region, EUROPE) per year:

  $$NF_i = \left(\frac{Impact_{i,EU}}{P}\right)^{-1} \qquad (11)$$

where, i is the considered impact category, P is the European (EU-27) population equal to 499M inhabitants[201].

3.2.3.3 Cost assessment

This provides a detailed breakdown of all the costs involved in the production systems under analysis. It hence enables a comparison between the two systems analysed in terms of cost efficiency. The production cost is calculated for both emerging and conventional systems on the basis of the inventorial information defined through the LCI. Each chemical, activity or service involved in the production phase is included in the cost assessment. The prices related to these elements is obtained from various sources that are case-specific (e.g. Sigma-Aldrich, EUROSTAT (for electricity and labour cost), etc.). With regards to the cost of the chemicals, a correction factor is generally applied to the prices. This is done with the aim of taking into account the favourable quotations that can be obtained in the case of large bulk orders or in the case of tailored agreements with suppliers for large scale productions.

The evaluation of the economics of the production systems is based on Operational Expenses (OPEX), Capital Expenses (CAPEX), and Payback Period (PBP).

Specifically, OPEX comprises the cost of chemicals and cleaning agents involved in the syntheses, labour, energy consumption and waste management. The cost associated with a generic chemical i, for a year of production, is expressed as:

$$cost_i = \left(\frac{£}{kg}\right)_i * kg\ of\ chemical\ i\ used\ in\ a\ year\ of\ production.$$

CAPEX is estimated in accordance with the following methods, and the obtained values are subsequently averaged:

- Lang's correlation[202]; $C_T = F_{Lang} \sum_{i=1}^{n} C_{p,i}$, where C_T is the capital cost of the plant, $C_{p,i}$ is the purchased cost for the major equipment units, n is the total number of units, and F_{Lang} is the Lang factor.
- Percentage of Fixed capital Investment[203]

With regards to the PBP, this is calculated as $PBP_i = \left(\frac{(A_{NCI} - OPEX_i)(1-TAX)}{CAPEX_i}\right)$, where i is the production system considered, A_{NCI} is the annual revenue, and TAX is the applied tax rate. For the comparison of the PBP of emerging and conventional process, the ratio of their PBPs is calculated as follow:

$$\frac{PBP_{Conventional\ tech.}}{PBP_{Emerging\ tech.}} = A_{NCI}\left(\frac{1 - OPEX_{Conventional\ tech.}}{1 - OPEX_{Emerging\ tech.}}\right)\left(\frac{CAPEX_{Emerging\ tech.}}{CAPEX_{Conventional\ tech.}}\right) \quad (12)$$

This indicator gives an idea of the relative amount of time needed to recover the investment, and it is used for the comparison of the economic performances of the two production systems.

3.2.4 COMPARATIVE ANALYSIS

In this last phase, the results of the LCIA and cost assessment for both emerging and conventional production systems are compared and interpreted. Environmental impacts and costs are further examined by means of a scenario analysis, with the aim of quantifying the savings (in terms of environmental impacts and costs) that originate from replacing the conventional system with the emerging technology under different scenarios, or identifying the conditions (e.g. yield of a step of the synthesis, efficiency of the recirculation system, etc.) under which the emerging technology would bring advantages over the conventional system and, and hence be deployed. In the assessment, there are a number of uncertainties mainly attributable to the variability of the data collected and to the assumption made for the calculation of the data not directly available for the inventory. Consequently, the results of the LCIA and cost assessment are affected by errors that arise from such uncertainties and that need to be quantified. To this end, an uncertainty analysis is performed for the results of the life cycle impact assessment and the cost assessment.

With regards to the LCIA, the environmental impact is composed by the contribution of various activities occurring in the life cycle (electricity generation, precursor production, etc.) that are organised in groups (chemicals, cleaning, energy consumptions, etc.). Each activity belongs to a specific group; thus, the sum of all the environmental impacts of the activities in a given group is equal to the environmental impact of that group. For example, the environmental impact of the group 'Chemicals' is the sum of the environmental impacts of the activities belonging to 'Chemicals', namely: the production of precursors, reducing agents, solvents, etc.. These groups are assigned a level of uncertainty (ε_j, with j being a given group) on the basis of the variability of the data collected and, on the assumptions made for the calculation of non-available data. Each one of these groups (chemicals, cleaning, energy consumption, etc.) contributes to the overall environmental impact of the production system in a different way for each impact category. The sum of the impacts of each group in a specific impact category is hence equal to the overall impact of the whole production system in that impact category. Therefore, an uncertainty error is calculated for each impact category; this uncertainty error is called $\varepsilon_{LCIA,i}$, with i being a given impact category. $\varepsilon_{LCIA,i}$ is calculated as the weighted sum of the uncertainty error (ε_j), with the weight being the % impact contribution of that specific group j in the impact category i considered:

$$\varepsilon_{LCIA,i} = \sum_j \left(\varepsilon_j * X_{i,j}\right)$$

where *i=impact category* and *j=group of the inventory* and $X_{i,j} = impact\ contribution$.

With respect to the cost assessment, the calculation of the uncertainty related is based on the same approach followed for the LCIA. More specifically, the following equation identifies the overall error related to the production cost (ε) as:

$$\varepsilon_{production\ cost,j} = \sum_{j} \left(\varepsilon_j * \frac{cost_j}{production\ cost} \right)$$

where *j is* the inventorial category.

Finally, when interpreting the results, it is worth considering that the inherent necessity of making use of scenarios and assumptions for the modelling choices during the assessment signify that the outcomes of an LCA of emerging technologies should not be regarded as the terminal result; it provides a set of expected answers and not the answer. The ultimate goal of this approach is in fact to lie the foundation necessary for debating and guiding research and development, and to provide a solid platform to discuss with all necessary stakeholders involved in the deployment of the technology.

3.3 THE CASE STUDIES

In the Thesis the proposed framework is put into practice and applied to four case studies that originate from both academic and industrial research and development. The case studies are briefly introduced below, and subsequently examined separately, in the next four chapters of the Thesis.

3.3.1 CASE I – FORMATE PRODUCTION FROM CAPTURED CO_2

The first case study looks into the production of formate using CO_2 captured from the tail gases of powerplants. CO_2 is potentially one of the most abundant feedstocks of chemical precursors that will be available in the next years. To this end, this case study explores the possibility to convert CO_2 into valuable chemicals, like formate, which opens compelling opportunities for simultaneously reducing greenhouse gases emissions and resource depletion in chemicals' production.

As part as the EPSRC UK project 'LCF' (Low Carbon Fuel), an innovative production system is being developed, based on the electro-catalytic reduction of CO_2 (ECR-IL) using an ionic liquid as solvent. The environmental impact of this system is quantified at lab scale (TRL 3) through the proposed framework, and benchmarked against the conventional production of formate from fossil fuels: the aim is identifying the intervention points in the process development for maximizing the environmental performance of the novel ECR-IL system, and understand under which conditions the novel system can result in performance gains over the conventional production.

3.3.2 CASE II - GOLD NANOPARTICLES PRODUCTION FOR NANO-ENABLED MEDICAL APPLICATIONS

The second case study focuses on the deployment of a milli-continuous-flow production of gold nanoparticles for healthcare applications; a product whose demand is increasing steeply in reflection of the recent advances in tumour targeting and diagnostics. In this respect, the study gives insights on the environmental impact and costs of the production of AuNPs for nano-enabled medical applications, by looking at two production technologies: a conventional batch production and an innovative milli-continuous flow production, currently at bench scale (TRL 4). The data originates from an experimental lab setup, developed in UCL's laboratories, as part of the objectives outlined in the EU project 'COSMIC' (European Training Network for Continuous Sonication and Microwave Reactors), and in the EPSRC UK project MAFuMa (Manufacturing Advanced Functional Materials).

3.3.3 CASE III – RUFINAMIDE PRODUCTION

The third study explores the effects of scale-up on a solvent-free and continuous-flow mini-pilot plant (TRL 4.5) for the production of Rufinamide, an anticonvulsant drug consumed worldwide for the treatment of epilepsy. The mini-pilot plant, shown in Figure 3.4, has been assembled at Microinnova GmbH (MIC) in Austria, and the assessment is fruit of a collaborative partnership between with the latter company.

Figure 3.4 - Picture of the mini-pilot plant at Microinnova GmbH (MIC) in Austria.

The environmental and economic performances of the novel technology are discussed and compared with the standard batch synthesis of Rufinamide. Both lab scale and mini-pilot scale setups were investigated in the assessment, and hence consideration on the effect of the scale up are drawn as well as projection on the future deployment of this production technology.

3.3.4 CASE IV - INTENSIFIED PRODUCTION OF ZEOLITE A

Finally, the fourth case study investigates the adoption of an intensified technology for the production of zeolite A. Specifically, the technology under consideration is continuous-flow synthesis using a continuous oscillatory baffled reactor (COBR). This production system is being developed by Arkema at GRL facilities in Lacq, and currently at full pilot-scale (TRL 5).

Figure 3.5 - Picture of the continuous oscillatory baffled reactor (COBR) developed by Arkema at GRL facilities in Lacq.

The emerging production system is benchmarked against a conventional batch production. Both systems are derived from Arkema's industrial facilities, by means of on-site data collection happened during an industrial secondment, as part as the project 'COSMIC'.

4 CASE I – FORMATE PRODUCTION FROM CAPTURED CO_2

The content of this Chapter was published in the Proceedings of Chemeca 2019 'Chemical Engineering Megatrends and Elements', including a supporting information document containing the inventory data of the work:

Pucciarelli, M., Grimaldi, F., Paulillo, A., Lettieri, P., 2019 Can the use of captured CO2 lower the environmental impacts of formate production?

4.1 CHAPTER SUMMARY

In this chapter the LCA methodology is applied to the assessment of an emerging technology that is currently being tested at lab scale (TRL 3). The aim of this first case study is to demonstrate the applicability of the framework presented in the previous chapter of the Thesis at this early stage of process development. Specifically, the environmental performances of the target technology are evaluated, and the results are analysed and discussed in order to:

- capture the uncertainties arising from applying the methodology very early – proof of concept stage at lab scale – in the technology development
- understand the usefulness of such results with regards to the optimization of the technology
- reach conclusions on the potentiality of such technology as alternative to conventional technologies.

The technology in question treats carbon dioxide and convert it into a valuable chemical – formate. To this end, the majority of bulk chemicals (e.g. olefins and alcohols) are organic compounds that are almost exclusively produced from fossil feedstocks such as natural gas. Utilisation of carbon dioxide captured from anthropogenic sources, which are both inexpensive and abundantly available, represents an alternative pathway that is drawing increasing attention, mainly for its potential to decreasing emissions of greenhouse gases and resource depletion of chemicals production. Notably, carbon utilisation does not represent an approach to CO_2 mitigation because it only delays its emissions rather than removing it over a long timescale; hence, the relevant question that we aim to address is: can captured CO_2 be used as feedstock to reduce the environmental impacts of chemicals' production?. As a case study, this work focuses on the production of formate and presents a prospective comparative life cycle assessment between the conventional fossil-based pathway and an innovative, CO_2-

based process that involves the electro-catalytic reduction of CO_2 using an ionic liquid as solvent. CO_2 is assumed to originate from a natural gas-fired power plant and captured after combustion, through a conventional monoethanolamine absorption system. Ionic liquids are used to enhance the reduction of CO_2 and its conversion to formate. The study adopts a cradle-to-gate perspective and analyses multiple impact categories including, but not limited to, global warming and resources depletion.

4.2 INTRODUCTION

The majority of bulk chemicals such as olefins and alcohols are organic compounds that are almost exclusively produced from fossil feedstocks such as oil and natural gas[204]. CO_2 captured from anthropogenic sources represents an alternative feedstock that has been receiving increasing attention in recent years, not only because it is an abundantly available and potentially inexpensive source of carbon[205–207], but also because it could reduce dependency on fossil fuels and carbon footprint of chemicals' production[208,209].

The reduction of greenhouse gas emissions is the single biggest challenge that humanity will face during the next decades. The latest IPCC report indicates that to achieve the more stringent target set by the Paris Agreement[210], equal to an increase of 1.5 °C in global temperature by 2100, anthropogenic emissions of carbon dioxide need to fall by 45% from 2010 levels by 2030 and to reach net zero by 2050[211]. Technologies that capture, utilise and storage carbon will play a key role in achieving this target, alongside other low carbon technologies such as renewable energies in the power generation industry and low carbon fuels in the transport sector.

In this work, we have applied LCA to understand the environmental performance of carbon capture and utilisation technologies for the production of bulk chemicals. The relevant question that we try to answer is: can captured CO_2 be used as feedstock to reduce the environmental impact of chemicals' production? The life cycle assessment methodology is instrumental to this end. LCA case studies for CO_2 utilisation have been published for chemicals' production such as methanol, methane, carbon monoxide and formic acid, and for conversion technologies such as catalysis, electro catalysis and photo catalysis[212–216]. Here we focus on an emerging technology using electrochemical conversion of CO_2 in a new type of ionic liquids (IL) to produce formate[217]. In addition, we integrate a power plant into the studied system, as source of CO_2. Formate can in turn be easily converted into formic acid, a widely used chemical in many industrial sectors including textile, agriculture, lather and farming. In 2014, global production capacity of formic acid stood at 950, 000 tonnes/year[218], with over 80% produced from hydrolysis of methyl formate from fossil feedstock. From 2019 to 2024, formic acid production is projected to grow at a compound annual rate of ~4%, especially in response to an increase in the demand in Asia[219]. Therefore, it is crucial to understand whether it can be possible to reduce its environmental impacts by using captured CO_2 as a feedstock.

This study is structured as follows: section 4.3 reports the LCA methodology, the goal and the scope of the study, and describes the product system; the results and discussion are presented in section 4.4, the main conclusions are summarised in section 4.5.

4.3 MATERIAL AND METHODS

4.3.1 FRAMEWORK

This study has a two goals. First, it quantifies the environmental impacts of producing formate through a novel process based on the electrochemical conversion of CO_2 captured from a natural gas power plan; it identifies the hotspots in the life cycle and proposes improvements. Second, it compares the environmental performance of CO_2-based formate production with the conventional process based on fossil feedstock with the aim of understanding the potential of using captured CO_2 to lower the environmental impacts associated with formate synthesis.

4.3.1.1 System definition

In this phase the process flow diagrams (PFD), material and energy flows are defined for the conventional and novel production systems. The batch system is sized on a commercial plant using fossil feedstock. With regard to the novel technology, the construction of the PFD is originated from an existing low-carbon production at lab scale based on the electrochemical reduction of CO_2 in ionic liquids. The full set of operations involved in a full-scale PFD is taken into account, namely, the precursors' preparation, IL production, pumping, synthesis, heating and mixing, cleaning, separation, recycling and waste disposal.

The resulting information is organised in the Life Cycle Inventory (LCI).

4.3.1.2 Assessment phase

- Life Cycle Inventory

  The electrochemical conversion of CO_2 in IL (ECR-IL) was modelled on the basis of primary data coming from laboratory experiments, along with literature data. For the modelling of the remaining processes, such as the production of ionic liquid, carbon dioxide capture, production of electricity, heat, and so forth, secondary data from both scientific literature and professional databases previously mentioned were used. A number of assumptions were required in order to perform the LCA study:

- the synthesis of formate is located in UK; hence, all related datasets used in the model refer to a UK based production;
- unless not already accounted in the dataset, transportation of goods was not considered in the model;
- the separation phase, composed of a gas/liquid separation and distillation, was integrated in the system, considering a highly optimised distillation column with a heat duty as low as 35 MJ/kg[208];
- 99.5% of acetonitrile and IL is recycled back to the electrochemical reaction phase; the resulting 0.5% is sent for waste disposal;
- the wastes coming from the separation phase are identified as hazardous wastes in accordance with the European regulation[220], and it is assumed that their disposal occurs via the incineration route.

The boundaries of the product system (see Figure 4.1) follow a “cradle-to-gate” approach; it includes all processes from extraction of raw materials up to the production of formate. The environmental impacts calculated refer to the production of 1 kg of formate; this is commonly the functional unit used in this case study.

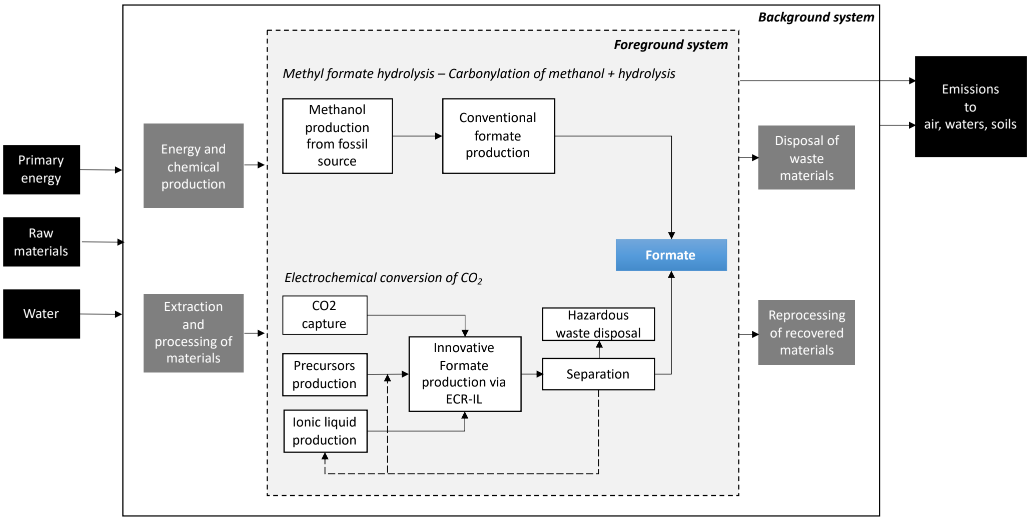


Figure 4.1 - System boundaries used in the LCA study.

- Environmental impact assessment

The conventional system was modelled using GaBi software[221], thinkstep (service package 36) and Ecoinvent (v. 3.6)[191] databases. Allocation is used in LCA to apportion the environmental impact to each function of a multi-functional process. The natural gas power plant with carbon capture introduced above is a multi-functional process because it generates electricity and also a stream of pure CO_2 that has economic value. In this work, we follow the ILCD (International Reference Life Cycle Data System) procedure for dealing with multi-functional processes[222]. For an attributional study and open loop recycling, the procedure envisages partitioning between the functions of the multi-functional process the environmental impacts of the process converting waste into valuable products. This is applied to the carbon capture process: it converts flue gas (waste) into a stream of pure CO_2 (valuable product). In this case, we calculate the partitioning factors based on the economic value of CO_2 and electricity; these are based on the average price of electricity in Europe, equal to 0.2 EUR/kWh[223] and on an estimated price of CO_2 of 15 EUR/ton based on[224]. Partitioning factors for electricity and CO2 are respectively equal to 0.97 and 0.03.

4.3.1.3 Comparative analysis

The results of the LCIA are further processed: the environmental impacts are examined through a hotspot analysis with the aim of identifying the steps in the production process that cause most of the environmental impacts. An uncertainty analysis is undertaken.

Finally, the output of these analyses, for the conventional and novel systems, are compared and discussed.

4.3.2 SYSTEMS DEFINITION

4.3.2.1 Electrochemical conversion of CO_2 in ionic liquid

The novel synthesis route of formate is a low-carbon production based on the electrochemical reduction of CO_2 in IL. More specifically, the procedure involves the utilisation of a super basic room temperature ionic liquid, namely trihexyltetradecylphosphonium 1,2,4-triazolide $[P_{66614}]$[124Triz], which enables a lower energy pathway to reduce CO_2, than other kind of ILs[217,225].

As shown in Figure 4.2, the process uses a platinum and a silver electrode immersed in 8 ml solution of acetonitrile, ionic liquid [0.1 M] and water [5.6 mM] to drive an electric current via an applied potential of 0.7 V, with CO_2 bubbled at a flow rate of 15ml/min. In these conditions, formate is produced with a Faradic efficiency of 95%[225].

Downstream of the reaction vessel, the solution is processed into the separation phase, comprised of a gas/liquid separation unit and a distillation column as reported in[208], in which the formate is separated and concentrated. The effluent of the separation, rich in acetonitrile and IL, is recirculated back into the system with an assumed recirculation ratio of 99.5% and mixed with fresh synthesis solution. The resulting waste stream coming out of the separation is treated as hazardous waste, which is collected and sent to incineration.

With regard to the CO_2 source, a plausible scenario was considered in which the CO_2 is captured from the flue gas coming out of a combined cycle power plant, using natural gas as a feedstock. More specifically, the CO_2 present in these exhaust gases is captured via absorption using monoethanolamine (MEA): 90% of the CO_2 in the flue gas is captured in this way[226], together with others pollutants, such as SO_2 NO_2, HCl and NH_3. Subsequently, the captured CO_2 is fed into the IL system. Although UK electricity generation is shifting from coal to renewable, the employment of natural gas has remained strong over the years, covering almost 40% of the national generation of electricity in 2018[227]. Such a scenario serves the purpose of contextualising these emerging technologies within the UK's decarbonisation targets.

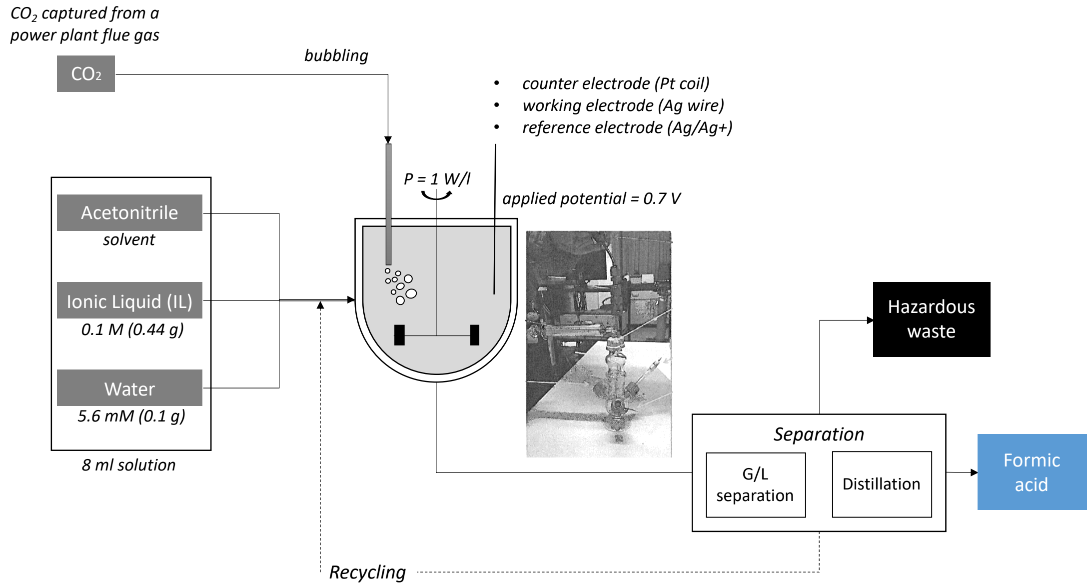


Figure 4.2 - Schematic of the foreground system for the electrochemical conversion of CO2 in formate at laboratory scale. The setup is being developed in the department of Chemical Engineering and Analytical science at the University of Manchester as part of the EPSRC UK project LCF.

4.3.2.2 Conventional formate production: methyl formate hydrolysis

The reference system is based on the conventional production of formate, synthesized via hydrolysis of methyl formate. The process hinges on fossil fuels, primarily natural gas[228], used as the main feedstock. Natural gas is converted into methanol that is subsequently subject to catalytic carbonylation by means of carbon monoxide. The resulting intermediate, methyl formate, is hydrolysed in presence of an additive (tertiary ammine) helping to overcome the unfavourable equilibrium of the hydrolysis and form formate[218].

The system described is used as the basis for the process benchmarking of the IL system. The resulting differences between the two production routes such as the type feedstock -fossil fuel versus a recycled CO_2 rich waste stream- are presented and assessed in the results and discussion section. The environmental impacts of the two systems are compared to understand the potential and drawbacks of the electrochemical conversion of CO_2.

4.4 RESULTS AND DISCUSSION

In the Life Cycle Impact Assessment (LCIA) phase results are calculated for all the selected impact categories. Each impact category represents an environmental issue of concern to which each material and energy flow can be assigned (ISO 14040:2006). In this study the results are calculated by using the ILCD method[229] and selecting the impact categories reported in Table 4.1.

Table 4.1 - List of the selected impact categories used for the calculation of the environmental impacts.

Impact category	Description	Unit	Abbr.
Acidification	It is mainly caused by air emissions of NH_3, NO_2 and SO_x.	[mole H^+ eq.]	A
Climate change, excluding biogenic carbon	Contributions of the greenhouse gases to the global warming and climate change	[kg CO_2 eq.]	CC
Ecotoxicity freshwater midpoint	Toxic effect on aquatic freshwater species in the water ecosystems.	[CTUe]	EcoTOX
Eutrophication freshwater midpoint	Eutrophication effects in the freshwater compartment.	[kg P eq.]	E fw
Eutrophication marine midpoint	Eutrophication effects in the marine compartment.	[kg N eq.]	E mw
Eutrophication terrestrial midpoint	Eutrophication effects in the terrestrial compartment.	[mole N eq.]	E t
Human toxicity midpoint, cancer effects	Toxic effect on humans referring to potential cancer effects.	[CTUh]	HT c
Human toxicity midpoint, non-cancer effects	Toxic effect on humans referring to potential non-cancer effects.	[CTUh]	HT non-c
Ozone depletion	Depletion of the ozone layer at the statosphere level.	[kg CFC-11 eq.]	OD
Photochemical ozone formation midpoint	Contributions of VOC (volatile organic compunds) and non-VOC to the formation of ozone at troposphere level.	[kg NMVOC eq.]	POF
Resource depletion, water	Water resource depletion.	[m^3]	RD water
Resource depletion, fossils and renewables	Depletion of mineral and fossil resources.	[kg Sb eq.]	RD m, f, ren

4.4.1 TECHNOLOGY COMPARISON

Figure 4.3 includes a comparison between the environmental performance of formate obtained via electrochemical conversion of CO_2 (named low carbon production in the chart) and via the conventional process based on the hydrolysis of methyl formate. On the x-axis the graph reports impact categories (the lower axis and metrics on the upper axis refer to Table 4.1).

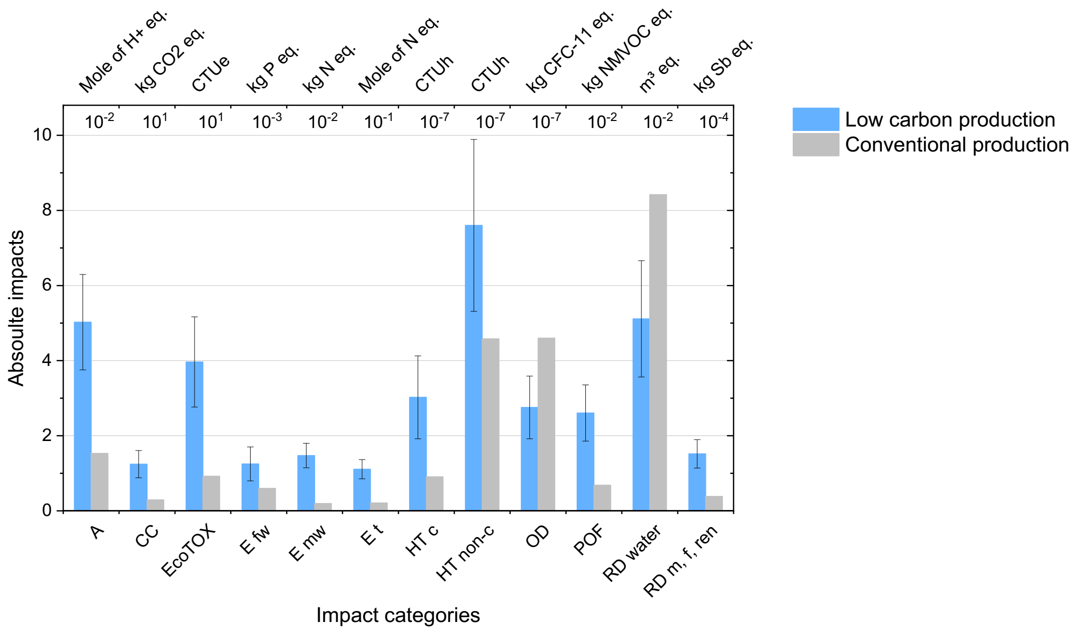


Figure 4.3 - Comparison of environmental impacts between ECR-IL system (low carbon process) and traditional process of formate production.

The comparison shows that the conventional process performs better than the low carbon one in all categories (including the climate change category) but the ozone depletion and water consumption categories, for which the impact of the low carbon process is ~40% lower. For the remaining impact categories, differences between the two systems range from 1.7 times in the human toxicity (non-cancer effects) category up to 7.6 times in the marine eutrophication category.

The low environmental performance of formate via ECR-IL process should not be surprising. Electrochemical conversion of CO_2 is a process thus far only implemented at laboratory scale with the objective of demonstrating its feasibility and efficiency. The process is thus not optimised in terms of consumption of energy and chemicals and it does not benefit from the economy of scale. On the other hand, the production of formate via hydrolysis of methyl formate is a well-established process implemented at commercial scale and optimised through decades of operation. However, the comparison is useful because it gives an understanding of the environmental performance that the electrochemical conversion process needs to achieve in order to become environmentally preferable.

4.4.2 HOTSPOTS ANALYSIS

In Figure 4.4 we report a hot-spot analysis on the electrochemical conversion process showing contributions of each element (e.g. electricity, ionic liquid, acetonitrile) of the system to the overall score in each environmental impact category. The chart shows that the contributions of each element vary substantially depending on the environmental issue considered. For instance, ionic liquid [P_{66614}][124Triz] contributions range from 6% in the climate change category up to 60% in the ecotoxicity category.

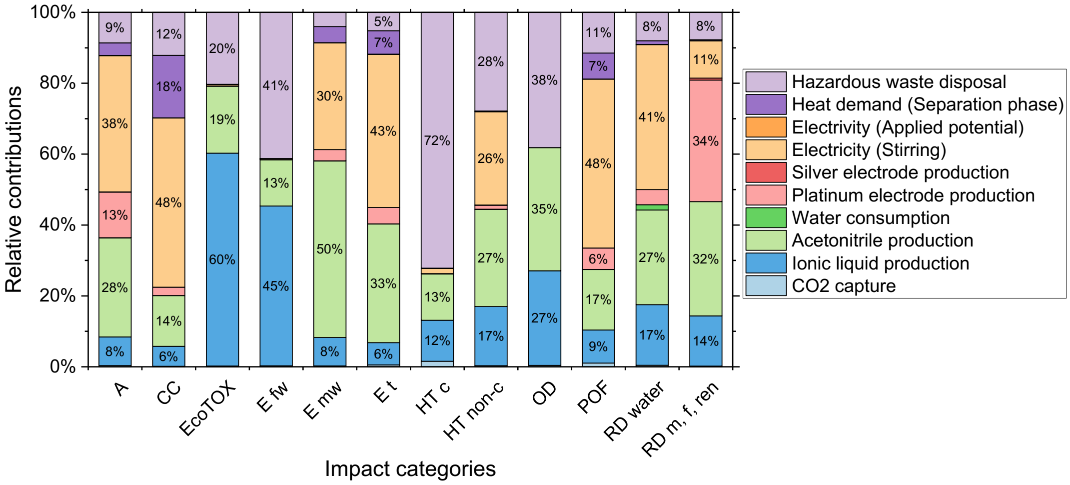


Figure 4.4 - Hot-spots analysis of the elements of the system contributing to the environmental impacts of the low carbon production.

Overall, the greatest portion of environmental impacts is due to production of acetonitrile, production and disposal of ionic liquid, and production of electricity used for stirring. For all, the primary cause is the considerable amount that is required for producing 1 kg of formate; this is expected to diminish when moving from laboratory to commercial scale. Furthermore, the environmental impacts of ionic liquid production are primarily attributed to the substantial amount of chemical required for its synthesis[230].

With respect to the other elements that are part of the product system, platinum electrodes play a significant contribution for the categories related to resources' depletion and acidification (respectively ~34% and ~13%); whilst thermal energy for the separation phase contributes to approximately a fifth of the impact in the climate change category. The remaining elements which include electricity used to drive the reduction of CO_2, silver electrode, water consumption and CO_2 capture have negligible contributions (lower than 2%). Notably, the small contribution of the CO_2 capture process is due to the price of CO_2 being significantly lower than that of electricity; this entails that only 4% of the environmental impacts of the carbon capture process are allocated to formate production (see section 4.3).

4.5 CONCLUSIONS

This first case study has given a preliminary overview of the environmental performances of an emerging technology at the nascent stages of the process development. Due to the low technological maturity of the target system (TRL 3), the outcome of this work is expected to be primarily used as basis to identify the intervention points in the technology development in order to minimize the environmental impacts. In fact, the uncertainties of the results associated to this novel production system are inherently high as the process is still far from reaching its final and optimized design: this was anticipately captured in Chapter 3 (precisely in Figure 3.1). Notwithstanding this, the comparison of the projected environmental impact of the novel IL production system with conventional production based on fossil fuel is helpful to understand the current limitation and future potentiality of the new technology.

To this end, this study presented a life cycle assessment of the production of formate via electrochemical conversion of CO_2 captured from a natural gas power plant. The LCI was derived from a laboratory scale data for the electrochemical conversion process and on literature data for the other processes.

The comparative analysis between formate obtained via electrochemical conversion of CO_2 and the conventional process based on hydrolysis of methyl formate showed that the latter is environmentally preferable in the majority of environmental categories, including climate change. The hot-spot analysis revealed that the greatest environmental impacts related to the electrochemical conversion process are due to production of electricity used for stirring, to the production of acetonitrile and to the production and disposal of ionic liquid. These impacts are expected to diminish when moving from laboratory to commercial scale. As shown in the hotspots analysis, it is crucial to optimize the recirculation system of the IL setup, in order to reduce the generation of hazardous wastes and avoid incineration of the latter. To this end, future works should be primarily directed at further optimizing these steps of the electrochemical conversion process; this is paramount in order to fully evaluate potential environmental savings when deployed at commercial scale compared to the traditional process.

In the next chapter, the assessment is performed on a production technology in a more mature stage of the process development. Specifically, it will be shown how moving from TRL3 to TRL 4 (bench scale) – thus targeting a system with higher technological maturity - positively affects the construction of the LCI and opens to a wider spectrum of projections and considerations regarding the deployment of the system under analysis.

5 CASE II - GOLD NANOPARTICLES PRODUCTION FOR MEDICAL APPLICATIONS

The content of this Chapter was published in the Journal of Cleaner Production, including a supporting information document containing the inventory data of the work:
Grimaldi, F. Pucciarelli, M., Gavriilidis, A., Dobson, P., Lettieri, P., 2020. Anticipatory Life Cycle Assessment of Gold Nanoparticles Production: Comparison of Milli-Continuous Flow and Batch Synthesis

5.1 CHAPTER SUMMARY

In the previous chapter, the framework for the assessment of emerging technologies was applied to a novel technology at the nascent stages of the process development. In this chapter the framework is tested on a process that is in a more advanced phase (TRL 4) - bench scale. Thanks to the higher maturity of the process, the knowledge and data availability on the latter process offers wider possibilities for its assessment. Specifically, the environmental impacts assessment is coupled with a cost analysis that is undertaken with the aim of extracting information on the economics of the process, thus adding a different angle to the evaluation of the system under analysis. The objective is to investigate the attractiveness of the novel process to potential investors for its eventual deployment, and benchmark it against a conventional production technology.

The target of the analysis is a new production system for gold nanoparticles. Currently, the demand of gold nanoparticles (AuNPs) is growing steeply as a result of the remarkable advances in the applications of this product in the healthcare and diagnostics sectors. To this end, having an efficient and sustainable production system is of paramount importance for achieving low environmental impacts and avoiding depletion of capitals. In this respect, the analysis gives insights into the environmental impact and costs of the production of AuNPs for nano-enabled medical applications, by looking at two production technologies: the conventional batch production and an innovative milli-continuous flow production, currently at lab scale. LCA and cost assessment are used to evaluate the sustainability and economics of the continuous-flow technology in an anticipatory fashion: this means capturing the environmental impacts and production costs of the emerging technology before it reaches full-scale and is deployed. The aim is to prevent waste of resources in the process development

and avoid having a non-optimized final system, which would lead to high costs and reduce competitiveness. The milli-continuous flow production was subjected to a scale up/out-analysis enabling the comparison with the batch production, already established at large scale. The life cycle of both production systems is described, and the results of the assessment comprise a normalisation analysis, which frames the environmental impacts of the gold nanoparticles production in the European context, a scenario analysis, a comparative analysis and a hotspot analysis. The results show that significant advantages can be gained from the adoption of the continuous-flow production in place of the batch system, both in terms of environmental impact and production costs. Specifically, the environmental impact is reduced in terms of human toxicity (cancer effect), ecotoxicity of freshwater and depletion of gold resources; these impact categories were identified as the main carrier of the environmental impact in the conventional production. The main contributors to savings for the flow production are primarily milder cleaning procedures, reduction of hazardous wastes produced, and less labour required for the operation and control of the process. Finally, the depletion of gold resources associated to the production of AuNPs emerges as a major issue. It is hardly addressable by using second-hand gold, and this calls for the necessity of recycling the product at the end of its life cycle or complementing AuNPs with alternative nano-products.

5.2 INTRODUCTION

In the last two decades, gold nanoparticles (AuNPs) have captured the attention of academic researchers and industries. The number of AuNPs related papers published since 2000 has reached the astonishing number of 50,415 and half of these have been published during the last 5 years (according to Thomson Reuters' Web of Science database; search conducted in March 2020). The area of interest spans from electronics to medicine. Several publications have reviewed the advances and perspectives of AuNPs in these fields by summarising their immunological properties[231] and their use in biomedicine[232], by focusing on synthesis methods[233], or by exploring their use in drug delivery[234] and sensing applications[235]. With their unique chemicophysical properties, either optical[236] or unexpected magnetism[237], AuNPs are suitable candidates for being used in healthcare fields such as in diagnostics[238,239] and cancer treatment[240]. To this end, AuNPs have been widely implemented as one of the leading nanomaterials for combinatorial cancer therapy[241]. For instance, AuNPs emerge as a particularly promising platform to combine photothermal and chemotherapy by co-incorporating AuNPs as photothermal agent, with cisplatin as anticancer drug, into alginate hydrogel[242,243], or by amplifying the effectiveness of chemotherapy and chemoradiation with plasmonic nanobubbles[244].

Accordingly, the global market for nanoparticles in the life sciences is forecast to reach USD 97.4 x 10^9 by the end of 2020 registering a healthy compound annual growth rate (CAGR) of 22%[245]. The biggest increase is expected to come in the area of drug delivery: AuNPs based applications are estimated to represent a 21% share of the total market of nano-drug delivery applications by 2021[246]. As a consequence of this, gold nanoparticle production has been increasing at a sustained rate to match the fast-growing demand of the product. In 2015, on the basis of both nano-enabled medical applications that either were on the market or had the potential to be introduced in the market, the annual mean prospective use of AuNPs for the UK and US was estimated to be around 540 kg and 2700 kg respectively, with tumour targeting and drug delivery being the main contributors (75% and 24% respectively)[247]. According to WHO's prediction, annual cancer cases are expected to increase from 16.4 M in 2018 to 22 M in 2032[248,249]. Considering an average amount of 5000 mg/person for the whole treatment cycle[247], the employment of gold nanoparticles could potentially reach 110 t/y in 2032.

Each year approximately 2,500-3000 t of gold are extracted. At present the total amount of above ground gold stocks is 190,040 t being divided among: jewellery (47.7%), private investment (21.1%), official sector (central banks) (17.1%) and other (14.1%)[250]. Below ground gold reserves are estimated to be around 54,000 t[251,252]. Should the gold stocks above ground be represented visually, they would appear as a 15-floor building, with below ground reserves being equivalent to an extension of mere four additional floors (Figure 5.1).

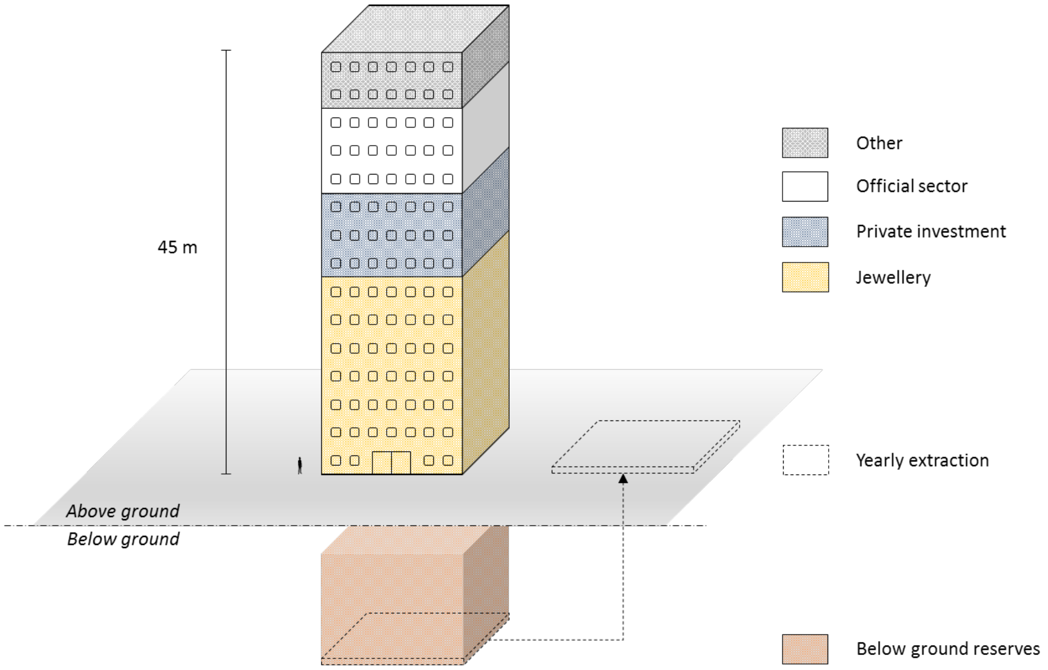


Figure 5.1 - Gold stocks distribution: visual representation of above and below ground gold stocks.

The extraction costs are increasing[253], ore grade have been decreasing over the last decade[254] and there are thoughts of having surpassed the peak gold: date at which the maximum rate of gold extraction is reached[255]. Furthermore, the volumes required to sustain the gold nanoparticles industry are limited [256], even though the demand is steeply going up[257].

In the light of current and potential applications, growing markets and gold availability, a rigorous analysis of the production routes of AuNPs is needed. To this end, a holistic method such as Life Cycle Assessment, complemented with a cost analysis, serves this purpose by covering most of the critical aspects of a production cycle. In this work, the LCA methodology is applied to an emerging technology, namely a milli-continuous flow production of AuNPs via the Turkevich method with the aim of providing a prospective assessment of such production technology at large scale and hence understanding the consequences of its full exploitation. The conventional method of gold nanoparticle production is batch-type. On the other hand, micro/milli-continuous flow (CF) technologies are innovative solutions in the synthesis of nanoparticles[258,259], and more generally in the intensified synthesis of chemicals[260]. These type of CF technologies are largely investigated because of their attractive features, such as high controllability of the product quality, ease of operation and scalability[261], and efficiency in the recovery of energy and in the reduction of wastes[26]. To this end, the transition from batch to CF production is a process intensification step that is currently being looked at in great detail by many academic and industrial sectors (i.e. COSMIC project as part of the Horizon 2020 programme[24]).

With regard to the synthesis method, the Turkevich method has been one of the main routes of synthesis of AuNPs for many years[262]. Recently, as result of the growing application of AuNPs, this synthesis method has received renewed attention with the aim of investigating more in depth the role of pH in the synthesis[263,264] and on the growth-mechanism[265], exploring the possibility of in-situ characterisation[266], and intensifying the synthesis through continuous-flow systems[267] as opposed to conventional batch systems. To this end, the sustainability of new intensified systems needs to be assessed in order to capture the future potentiality of these systems. In research-intensive industries (i.e. healthcare), it is paramount to filter emerging technologies at early stages to prevent waste of resources, which leads to high costs and reduce competitiveness. Not all processes reach in fact commercial scale, and this turns into loss of human and capital resources. Furthermore, early assessments can grasp the consequences of adopting such systems after the scale up/out to commercial scale, in place of conventional production systems.

LCA can be used in this respect to provide a faithful evaluation of the environmental impact of innovative production systems in an anticipatory fashion[135,268], at the early stages of the process development. To the best of the authors' knowledge, no LCA and cost assessment on gold nanoparticles production systems at large scale have been published yet. Currently available publications consider only syntheses at lab scale[269] either focusing on different recipes[270,271] or nano-waste recovery[272], but without investigating a full scale production inclusive of high impacting peripheral steps such as cleaning or waste disposal[273], or offering a comparison with conventional production systems. Therefore, the whole life cycle of the production of gold nanoparticles needs to be properly assessed prior to its large-scale deployment in consequence of the imminent growth of gold nanoparticles demand. This type of assessment would help establishing optimized production plants[274] and hence prevent waste of resources which is usually synonymous of high costs and high environmental impacts.

LCA and cost assessments are used in this work to interlace three macro topics, namely sustainable development, process intensification and scale-up of emerging technologies. The synthesis of AuNPs is investigated by taking into consideration two production systems, batch and milli-CF. The batch system mirrors a standard industrial production, hence it is taken as the reference case, while the continuous flow system is extrapolated from the lab scale, scaled up/out and benchmarked against the batch production at large scale. Both production systems refer to the synthesis of 10 nm gold nanoparticles- of Optical Density 1 (OD1), produced via the Turkevich method- a product that is used intensively in nano-enabled medical applications. The whole set of operations typically involved in an industrial plant are considered: cleaning, separation, energy and material recovery. In addition, the modelling of the life cycle of the production systems comprises all the peripheral activities supporting the synthesis of gold nanoparticles, such as the production of chemicals, energy generation, raw material extraction and waste treatment.

On the whole, the primary goal of the present study is to give insights on the environmental impact and cost of batch and CF production at large scale, and investigate on how sustainable the full exploitation of AuNPs products in nano-enabled medical applications would be in the near future.

5.3 MATERIAL AND METHODS

5.3.1 FRAMEWORK

The basic structure of this work is represented in Figure 5.2. It consists of three main phases, namely, system definition, assessment and comparative analysis, on the basis of the framework presented in section 3.2.

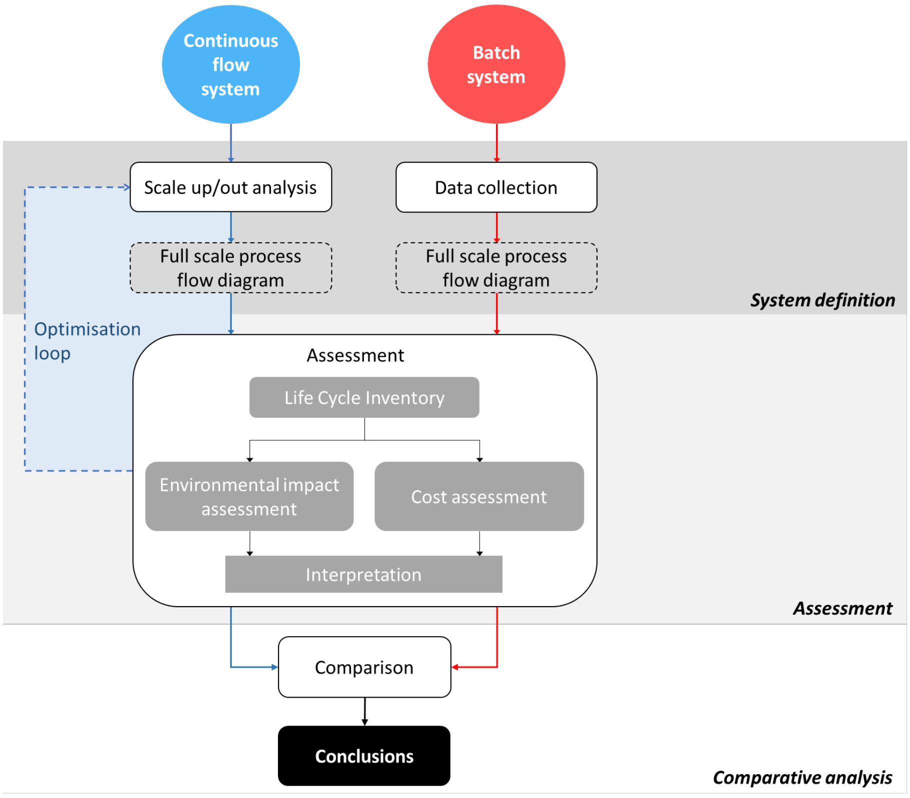


Figure 5.2 - Framework: system definition, assessment and comparative analysis.

5.3.1.1 *System definition*

In this phase the process flow diagrams (PFD), material and energy flows are defined for both the continuous flow and batch system. The batch system is designed to represent a typical commercial production scale (approximately 45 m^3 of AuNPs product, OD1 namely 5.76×10^{-2} mg/ml, with a maximum coefficient of variation of 10%, equivalent to 2.5 kg of dry gold nanoparticles per year) and its scale is used as the reference to which the continuous flow system is based on. With regard to the latter, the construction of the PFD originates from a lab scale and brought, through a scale up/out study, up to a commercial scale matching the reference (batch) productivity. The full set of operations involved in a full-scale PFD is taken into account, namely, the precursors' preparation, pumping, synthesis, heating and mixing, cleaning, separation and waste disposal.

5.3.1.2 Assessment phase

- Life Cycle Inventory

The chosen FU for this study is 1 litre of AuNPs product (OD1, 10 nm) obtained from a yearly production of 45 m^3 of product.

The data for the LCI are quantified for each unit process included into the defined system boundaries (Figure 5.3). The foreground system comprises the array of operations occurring in the production phase, separation, cleaning and waste processing. The background system is composed of the set of operations and services that revolve around the synthesis, and whose impacts were taken into account in the assessment: electricity production, raw materials extraction, chemical production and waste disposal. Each process has been built into the model by compiling the material and energy balances occurring in them (see section 3.2.3.1).

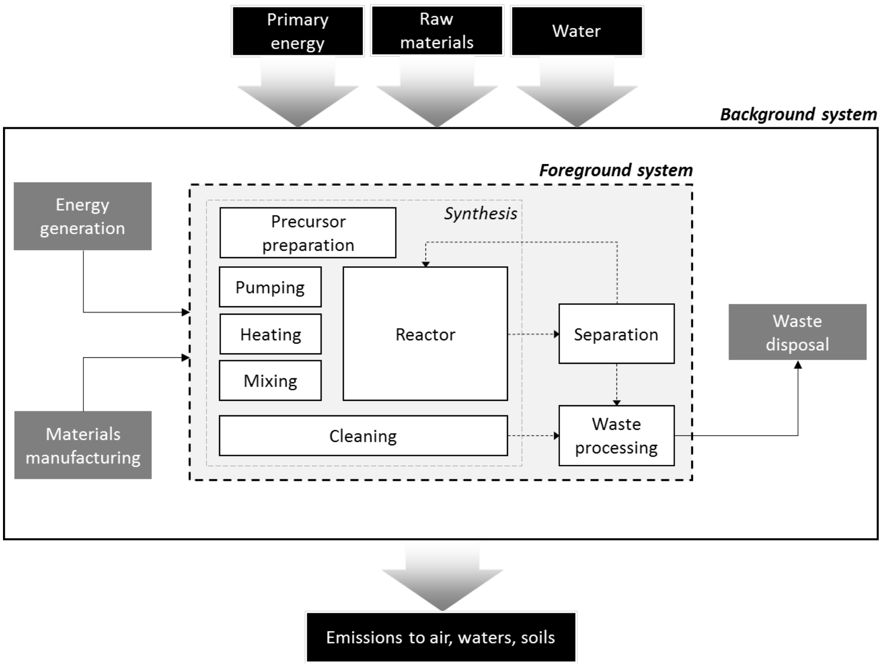


Figure 5.3 - System boundaries: foreground and background systems.

The functional unit and the system boundaries defined are the same for both continuous flow system and batch system, this is a *sine qua non* condition for a coherent comparison.

- Environmental impact assessment

The environmental impacts of the batch and continuous flow production systems are calculated. ILCD/PEF recommendation 1.09[72] is the chosen method for the LCIA, in accordance with the framework presented in section 3.2.3.2. Results are grouped in midpoint categories. The database used for the model is GaBi ts 8.7 (SP36) professional + extensions (II, VI, IX, XVII) and Ecoinvent 3.6 (integrated SP36). The LCIA results are expressed on the basis of the chosen FU – specifically 1 litre of AuNPs product (OD1, 10 nm) obtained from a yearly production of 45 m^3 of product. In accordance to the ISO 14044, with regards to a comparative analysis, the functional unit is set to be the same for all the compared product systems. Environmental impacts were estimated using a cradle-to-gate boundary for European production. The impact categories selected for this study are reported in Table 5.1.

Table 5.1 - Impact categories used for the LCIA and description: the impact categories are selected from the LCIA method 'ILCD/PEF recommendation 1.09'.

Impact category	Description	Unit	Abbr.
Acidification	It is mainly caused by air emissions of NH_3, NO_2 and SO_x.	[mole H^+ eq.]	A
Climate change, excluding biogenic carbon	Contributions of the greenhouse gases to the global warming and climate change	[kg CO_2 eq.]	CC
Ecotoxicity freshwater midpoint	Toxic effect on aquatic freshwater species in the water ecosystems.	[CTUe]	EcoTOX
Eutrophication freshwater midpoint	Eutrophication effects in the freshwater compartment.	[kg P eq.]	E fw
Eutrophication marine midpoint	Eutrophication effects in the marine compartment.	[kg N eq.]	E mw
Eutrophication terrestrial midpoint	Eutrophication effects in the terrestrial compartment.	[mole N eq.]	E t
Human toxicity midpoint, cancer effects	Toxic effect on humans referring to potential cancer effects.	[CTUh]	HT c
Human toxicity midpoint, non-cancer effects	Toxic effect on humans referring to potential non-cancer effects.	[CTUh]	HT non-c
Ionising radiation	Human exposure to ionizing radiation with potential alterations in the DNA	[kBq U235 eq.]	IR
Ozone depletion	Depletion of the ozone layer at the stratosphere level.	[kg CFC-11 eq.]	OD
Particulate matter	Direct and indirect contribution to particulate matter formation	[kg PM2.5 eq.]	PM
Photochemical ozone formation midpoint	Contributions of VOC (volatile organic compounds) and non-VOC to the formation of ozone at troposphere level.	[kg NMVOC eq.]	POF
Resource depletion, water	Water resource depletion.	[m^3]	RD water
Resource depletion, minerals, fossils and renewables	Depletion of mineral and fossil resources.	[kg Sb eq.]	RD m, f, ren

- Cost assessment

This provides a detailed breakdown of all the costs involved in the production of AuNPs. The production cost is calculated for both batch and continuous flow system on the basis of the inventory information defined through the LCI. Each chemical, activity or service involved in the production phase is included in the cost assessment. The list of the prices related to these elements is reported in Table 5.2.

Table 5.2 - Breakdown of the prices related AuNPs production via Turkevich method: prices associated to materials, equipment, labour and waste disposal activities for batch (B) and continuous flow system (CF).

Groups	Item	Specific price	
Chemicals	$HAuCl_4$ trihydrate	45263	£/kg
	Trisodium citrate	31	
	Water	0.15	
	(CF) Heptane	80.35	
Cleaning	(B) Aqua regia	10	
	(B) IPA	1.71	
	(B) NaOH	12	
	Water	0.001	
Reactor equipment and service fluids	(B) Jacketed Batch (350 l)	25000	£/unit
	(B) Jacketed Batch (60 l)	15000	
	(B) Double Jacketed Batch (10 l)	6000	
	(CF) Teflon capillaries	7.46	£/m
	Silicone oil	7	£/kg
Peripheral equipment	Pumps	1436	£/unit
	(CF) Membrane separator	4000	
Energy consumption	Electricity (Heating)	0.11	£/kWh
	Electricity (Mixing)		
	Electricity (Pumping)		
Labour	Technicians	44	£/person*h
Waste disposal	Water treatment	3	£/m^3
	Hazardous waste	180	£/t

The source of data is mainly Sigma-Aldrich (for chemicals) and EUROSTAT (for electricity and labour cost). With regard to the cost of the chemicals, a correction factor is applied to the prices. This is done with the aim of taking into account the favourable quotations that can be obtained in the case of large bulk orders or in the case of tailored agreements with suppliers for large scale productions.

The correction factors are obtained as follows:

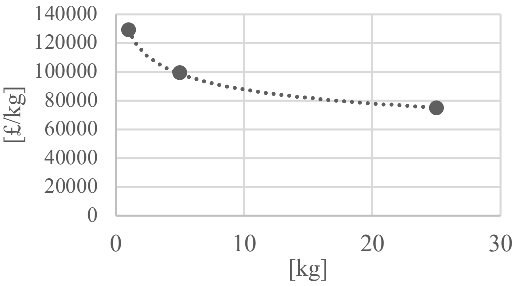
- The price of a given chemical is plotted against the quantity of the order according to the data coming from the suppliers.
- A power regression is performed on the data points
- The obtained trend-line is used to extrapolate the price of the chemical related to quantities higher than the highest available data point (the largest bulk order)
- The price extrapolated is that related to a maximum weight of chemical equal to 20 times the maximum weight of chemical orderable in bulk from that supplier; this cap is meant to limit the chances of underestimating the prices.

Here follow the calculations:

- Tetrachloroauric acid trihydrate

Considered bulk order: 500 grams equal to 45263 £/kg

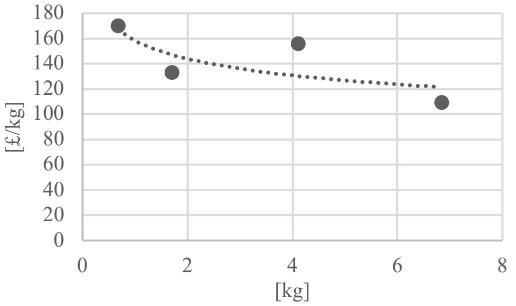
Price [£]	Quantity [g]	Specific price [£/kg]
129	1	129000
496	5	99200
1874	25	74960



- Heptane

Considered bulk order: 137 kg equal to 80.3 £/kg

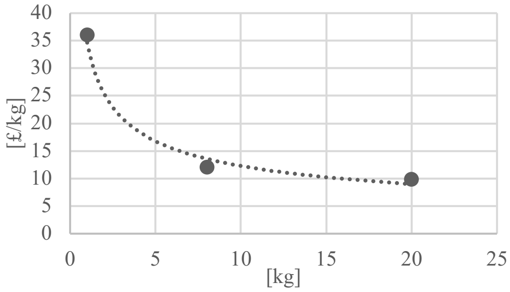
Price [£]	Quantity [g]	Specific price [£/kg]
116	0.684	170
228	1.710	134
641	4.104	156
750	6.840	110



- IPA

Considered bulk order: 800 kg equal to 1.71 £/kg

Price [£]	Quantity [kg]	Specific price [£/kg]
36	1	36
96	8	12
196	20	9.8



The evaluation of the economics of the production systems is based on Operational Expenses (OPEX), Capital Expenses (CAPEX), and Payback Period (PBP). Specifically, OPEX comprises the cost of chemicals and cleaning agents involved in the syntheses, labour, energy consumption and waste management. The cost associated with a generic chemical i, for a year of production, is expressed as:

$$cost_i = \left(\frac{£}{kg}\right)_i * kg\ of\ chemical\ i\ used\ in\ a\ year\ of\ production.$$

CAPEX is estimated in accordance with the following methods, and the obtained values are subsequently averaged:

- Lang's correlation[202]; $C_T = F_{Lang} \sum_{i=1}^{n} C_{p,i}$, where C_T is the capital cost of the plant, $C_{p,i}$ is the purchased cost for the major equipment units, n is the total number of units, and F_{Lang} is the Lang factor.
- Percentage of Fixed capital Investment[203]

CAPEX		Applied % factor	Batch system	Continuous Flow system
Direct costs	Purchased equipment	22.0%	£ 69,676	£ 72,827
	Purchased equipment installation	8.0%	£ 25,337	£ 26,483
	Instrumentation and control	4.0%	£ 12,668	£ 13,241
	Piping	9.2%	£ 29,137	£ 30,455
	Electrical	4.8%	£ 15,202	£ 15,890
	Buildings	8.4%	£ 26,604	£ 27,807
	Yard improvements	2.8%	£ 8,868	£ 9,269
	Service facilities	11.2%	£ 35,471	£ 37,076
	Land	1.2%	£ 3,801	£ 3,972
Indirect costs	Engineering and supervision	10.0%	£ 31,671	£ 33,103
	Construction expenses	7.2%	£ 22,803	£ 23,834
	Contractor's fee	3.2%	£ 10,135	£ 10,593
	Contingency	8.0%	£ 25,337	£ 26,483
	Tot Fixed capital investment	22.0%	£ 316,709	£ 331,033

With regard to the PBP, this is calculated as $PBP_i = \left(\frac{(A_{NCI} - OPEX_i)(1 - TAX)}{CAPEX_i}\right)$, where i is the production system considered, A_{NCI} is the annual revenue, and TAX is the applied tax rate. For the comparison of the PBP of batch and CF process, the ratio of their PBPs is calculated as follow:

$$\frac{PBP_{Batch}}{PBP_{Continuous\ flow}} = A_{NCI}\left(\frac{1 - OPEX_{Batch}}{1 - OPEX_{Continuous\ flow}}\right)\left(\frac{CAPEX_{Continuous\ flow}}{CAPEX_{Batch}}\right)$$

This indicator gives an idea of the relative amount of time needed to recover the investment, and it is used for the comparison of the economic performances of the two production systems.

5.3.1.3 Comparative analysis

The results of the LCIA and cost assessment are organised, and an uncertainty analysis is performed.

There are a number of uncertainties mainly attributable to the variability of the data collected and to the assumption made for the calculation of the data not directly available for the inventory (i.e. cleaning procedures for the batch system). Consequently, the results of the LCIA and cost assessment are affected by errors that arise from such uncertainties and that need to be quantified. There errors are hence calculated for: the results of the life cycle impact assessment and for the results of the cost assessment.

With regard to the LCIA, the environmental impact of the production system is expressed for a number of impact categories (see section 3.1). The environmental impact is composed by the contribution of various activities occurring in the life cycle (electricity generation, sodium citrate production, etc.) that are organised in groups (chemicals, cleaning, energy consumptions, etc.). Each activity belongs to a specific group; thus, the sum of all the environmental impacts or costs of the activities in a given group is equal to the environmental impact of that group. For example, the environmental impact of the group 'Chemicals' is the sum of the environmental impacts of the activities belonging to 'Chemicals', namely: $HAuCl_4$ production, sodium citrate production, heptane production and water use.

These groups are assigned a level of uncertainty (ε_j, with *j* being a given group) on the basis of the variability of the data collected and on the assumptions made for the calculation of non-available data. Each one of these groups (chemicals, cleaning, energy consumption, etc.) contributes to the overall environmental impact of the production system in a different way for each impact category. The sum of the impacts of each group in a specific impact category is hence equal to the overall impact of the whole production system in that impact category. Therefore, an uncertainty error is calculated for each impact category; this uncertainty error is called $\varepsilon_{LCIA,i}$, with *i* being a given impact category. $\varepsilon_{LCIA,i}$ is calculated as the weighted sum of the uncertainty error (ε_j), with the weight being the % impact contribution of that specific group j in the impact category i considered:

$$\varepsilon_{LCIA,i} = \sum_j \left(\varepsilon_j * X_{i,j}\right)$$

where *i=impact category* and *j=group of the inventory* and $X_{i,j} = impact\ contribution.$

With respects to the cost assessment, the calculation of the uncertainty is based on the same approach followed for the LCIA. More specifically, the following equation identifies the overall error related to the production cost (ε) as:

$$\varepsilon_{production\ cost,j} = \sum_j \left(\varepsilon_j * \frac{cost_j}{production\ cost}\right)$$

where *j is* the inventorial category.

In the comparative analysis, the environmental impacts are further examined through a scenario analysis, following the procedure reported in section 3.2.3.2. This contextualises the environmental impacts of the production of gold nanoparticles in the broader context of European emissions. It also provides a projection of the environmental impacts of the AuNPs production in the scenario in which gold nanoparticles are fully adopted in nano-enabled medical applications.

Specifically, the normalised impact (*NI)* is calculated by multiplying the impact of the product by the normalisation factor (*NF*):

$$NI_i = Impact_{i,tot} * NF_i$$

where, i is the considered impact category.

The chosen normalisation method is ILCD/PEF recommendation 1.09[201]: the normalisation factor is expressed in impact per person equivalents (*P,* representing the reference region, Europe) per year:

$$NF_i = \left(\frac{Impact_{i,EU}}{P}\right)^{-1}$$

where, i is the considered impact category, P is the European (EU-27) population equal to 499M inhabitants[201].

Furthermore, a hotspot analysis is also performed with the aim of identifying the steps in the production process that cause most of the environmental impacts.

Finally, the output of these analyses, for the batch and CF systems, are discussed.

5.3.2 SYSTEM DEFINITION

The full-scale process flow diagrams are presented in this section for the batch and the CF systems, describing the production phase of AuNPs in detail. The definition of these systems provides all the inventorial information for the LCI. The production phase is highly important for the description of the life cycle of AuNPs product. In fact, it determines all the peripheral activities that orbit around it, such as electricity production, waste disposal and production of chemicals, which are considered in the assessment.

In the assessed systems, the synthesis of AuNPs follows the Turkevich method. This has been one of the main routes of synthesis of gold nanoparticles for many years[262] and hence a large amount of data and knowledge on it is available in the literature. This literature-based information was used to complement the data from the lab experiments and from the industrial practice, in order to fully describe a full-scale production system for both batch and CF. In fact, on one side, the batch production is conventionally adopted for the production of gold nanoparticles at commercial scale, and the description of this system has been achieved mainly by means of data collection and only partly integrated with literature data to cover missing details. On the other side, the CF production system is an emerging technology and it has not been scaled up yet. The full-scale CF system described in this section is a projection, and therefore its definition required a lot of information based on lab experiments and on information available in the literature. The maturity of the continuous flow production system developed in the lab and complemented with the data coming from the literature[264–266] was adequate to enable a scale up/out analysis.

With regard to the details of the Turkevich method, the synthesis of gold nanoparticles occurs via reduction of tetrachloroauric acid trihydrate ($HAuCl_4$) by trisodium citrate (Na_3Cit). The target product is 10 nm gold nanoparticles suspended in water with optical density OD1, equal to 5.76×10^{-5} g_{gold}/l, and maximum coefficient of variability (CV, calculated by dividing the standard deviation of the nanoparticle size by the mean nanoparticle size) of 10%. The recipe adopted for both batch and CF synthesis is the same: $[HAuCl_4] = 0.5\ mM;\ \frac{mol\ Na_3Cit}{mol\ HAuCl_4} = 6$.

A schematic representation of the PFD of the two system is shown in Figure 5.4.

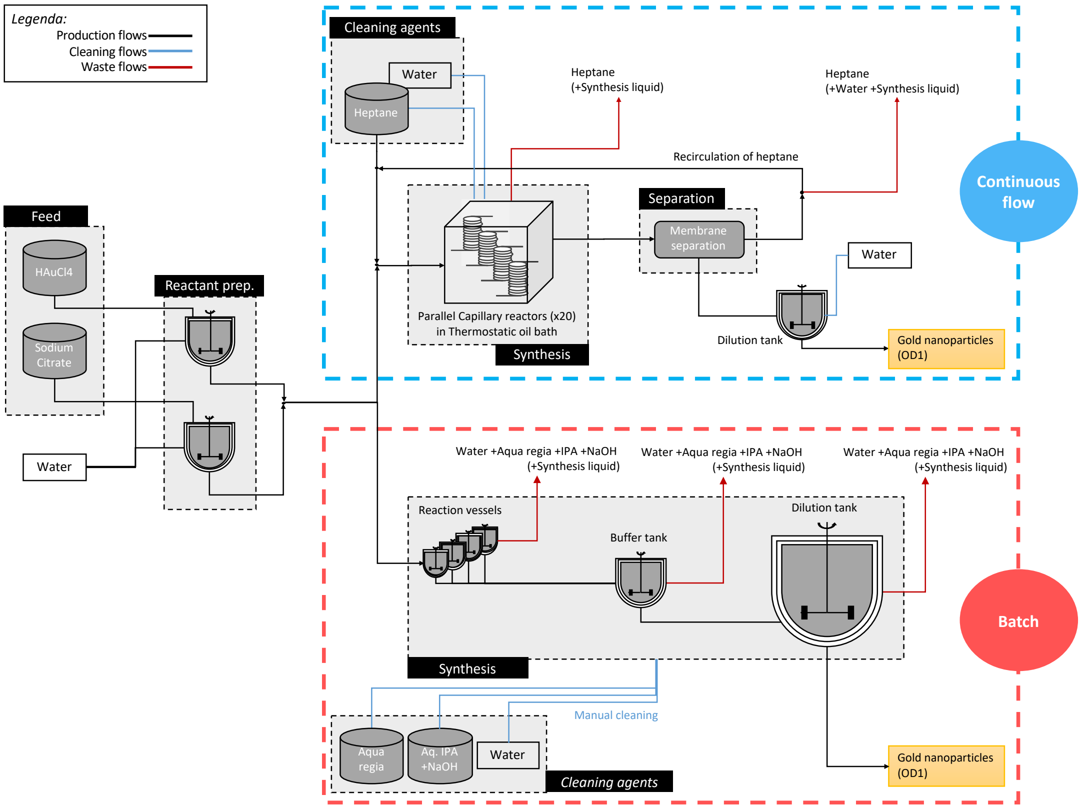


Figure 5.4 - Schematic representation of the process flow diagram of batch and continuous flow system.

There are a number of substantial differences in the PFD of the two systems. The CF setup involves a segmenting fluid, heptane, to achieve a Taylor flow in the reaction step. This is necessary in order to improve residence time distribution and avoid fouling that can affect product quality. Furthermore, a separation step is included in the CF system for the separation of the product from the segmenting fluid and the recirculation of the latter. The cleaning of the two systems also follows different procedures.

The summary of the LCI information regarding the batch and CF systems is reported in Table 5.3.

Table 5.3 - Inventory list for the batch and continuous flow system: materials, energy consumption and labour.

Groups	Item	Quantity		
		Continuous Flow system	Batch system	
Chemicals	$HAuCl_4$ trihydrate	4.33	4.33	*kg*
	Trisodium citrate	19.7	19.7	
	Water	44000	44000	
	Heptane	134.4	0	
Cleaning	Water	23010	289575	*kg*
	Aqua regia	0	223	
	IPA	0	43018	
	NaOH	0	7596	
	Heptane	95.7	0	
Reactor equipment and service fluids	Teflon capillary	120	0	*m*
	Silicone oil	3880	100	*kg*
Peripheral equipment	Membrane separator	1	0	*unit*
	Pumps	27	16	
Energy consumption	Electricity (Heating)	21609	1686	*kWh*
	Electricity (Mixing)	171	5081	
	Electricity (Pumping)	97306	20167	
Labour	Technicians	2920	5072	*person*h*
Waste disposal	Water treatment	1500	1500	m^3
	Hazardous waste	230	340	*kg*

In the next two sections the full description of the PFD of the batch and CF system is reported. This includes a quantitative and qualitative report of the procedure of cleaning and maintenance observed in the production systems, along with the full list of the material and energy inputs used in the LCI.

5.3.2.1 *Continuous flow system*

The full-scale process flow diagram of the continuous flow system is presented in Figure 5.5.

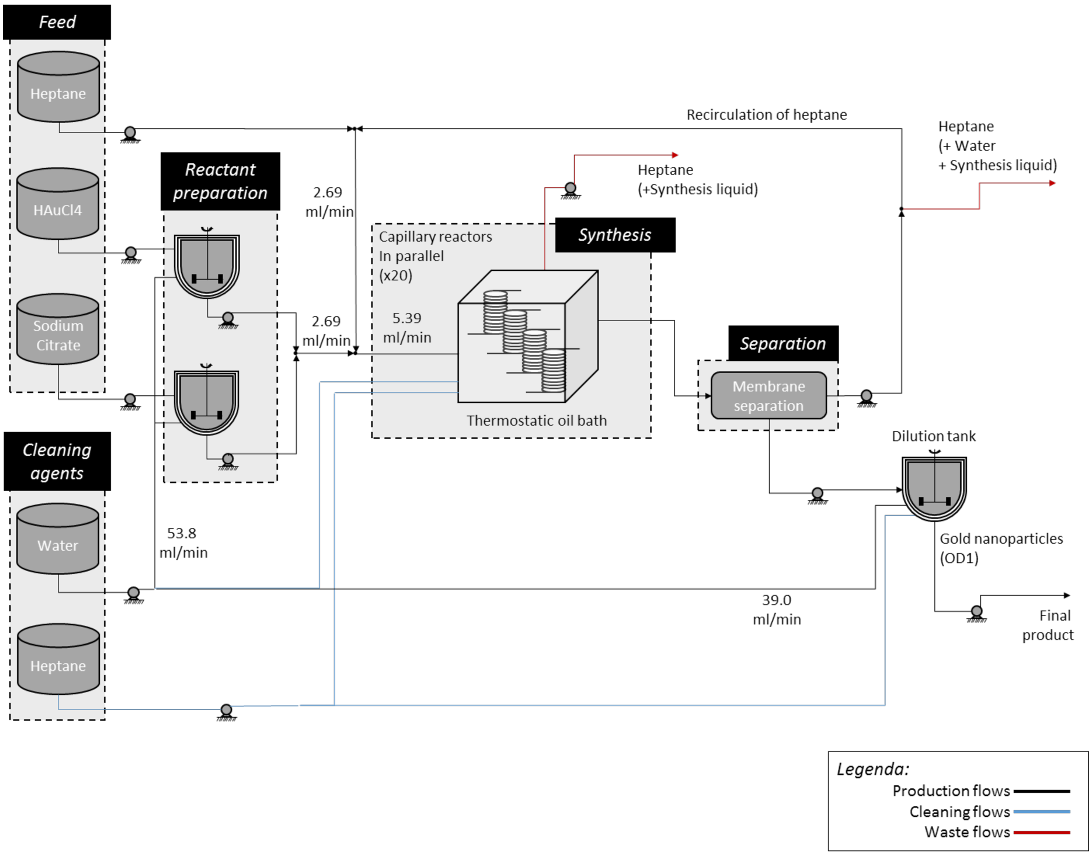


Figure 5.5 - Overview of the continuous flow production system for AuNPs: process flow diagram.

This was obtained starting from the lab setup and designed conceptually at large scale by means of a scale up and scale out analysis. The scale up/out was based on both considerations arising from lab experiments and from a literature research on milli-fluidics and AuNPs synthesis. Specifically, in the lab configuration, the gold precursor and sodium citrate are first mixed and then introduced to a pure heptane stream in a Teflon capillary reactor with an Internal Diameter (ID) of 2.4 mm. The flow regime is Taylor-type and the two phases have a volume ratio 1:1, with the total flowrate being equal to 1 ml/min. The residence time in the capillaries affects the size of the nanoparticles. In this case, the target diameter of the nanoparticles is 10 nm, corresponding to a residence time of 5 min and a capillary length of 5.96 m. The two phases, synthesis fluid and segmenting fluid, are fed into the reactor where the growth of AuNPs is achieved at 100 °C. The kinetics and the flow regime characterising the lab setup were preserved during the scale up/out by keeping fixed the residence time, the ID of the reactor, and the flowrate ratios. Specifically, the residence time was not affected by the scale up as the total flowrate and the reactor length were changed accordingly. The total flowrate was increased; this scaled-up flowrate is in the region of flowrates in which the Taylor flow regime is preserved. The flow is in fact composed by two liquid phases, the precursor solution and the segmenting fluid, and an emulsion of these fluids is unwanted for reasons of residence time distribution and fouling. At the scaled-up flowrate, 5.39 ml/min, and ID of 2.4 mm, the resulting flow regime is conserved, and no emulsion is occurring. The length of the reactor has negligible effects on the flow regime and hence it was set on 5.96 m in order to have the same residence time as the lab experiments. After the scale up analysis, the scale out analysis was performed following a numbering up criterion that is a standard practice in micro/milli-fluidics[27,260,275–278]. A set of twenty capillary reactors operating 24/7, were designed to operate in parallel, each one having the characteristics used in the scale up phase (see Table 5.4).

Table 5.4 - Details on the continuous flow reactors for AuNPs: volumes and flowrates of synthesis, heptane and water streams

Flowrates*	**Production phase**	**Cleaning phase**	
		I	II
	ml/min	*ml/min*	*ml/min*
Total (20 reactors)	107.8	107.8	107.8
Synthesis fluid	53.9	0	0
Heptane	53.9	107.8	0
Water	0	0	107.8

*duration of production and cleaning are given in Table 5.5

Volumes	*ml*
Total (20 reactors)	539
Reactors + pipes	1078

The heating system is composed of five silicone oil baths, accommodating four reactors each. The temperature setpoint is 100 °C. The production is continuous, and therefore the thermostatic baths are not affected by any sort of cyclical temperature ramp up and cool down, as happens in the batch system. The ramp up and cool down of temperature took around 55% of the total heat duty in the batch system. Notwithstanding this, the batch system showed a lower heat duty than the CF system, mainly because the total volume of the batch reactors is lower than the total volume of the continuous flow reactors. This is because, in the batch system the synthesis liquid is more concentrated than the synthesis liquid of the CF system. There are two reasons behind the difference of concentration. On the one hand, in the batch system, the dilution step is downstream of the reaction phase and hence lower volumes of synthesis fluid are heated. On the other hand, in the CF system, the synthesis fluid is composed of an additional phase, the segmenting fluid (heptane), and hence more volume is flowed into the reactors representing an added burden to the heating system.

The total heat duty $E_{heating}$ is given by:

$$E_{heating} = a * E_{ramp\ up} + E_{production} \qquad \text{being } a = \begin{cases} 0 & if\ CF \\ 1 & if\ Batch \end{cases}$$

where $E_{heating}$ is the total energy required for the heating of the system, $E_{ramp\ up}$ is the energy required for the ramp up of the temperature during the start-up of a production cycle and

$E_{production}$ is the energy required for keeping the setpoint temperature of 100 °C during the production.

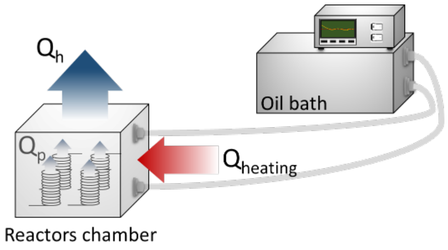


Figure 5.6 - Heating system in the continuous flow system: visual representation of a set of capillary reactors in a thermostatic oil bath

$$\frac{dQ_p}{dt} \ll \frac{dQ_h}{dt}$$

where, Q_p is the heat flow through the walls of the capillaries and Q_h is the heat flow through the walls of the thermostatic chamber. Consequently, the resulting heat flow through the chamber is calculated as:

$$\frac{dQ_{heating}}{dt} = \frac{dQ_h}{dt} = hA(T_{medium} - T_{env})$$

$$E_{production} = hA\Delta T * t$$

$$E_{ramp\ up} = mc_p\Delta T$$

Specifically:

$$\frac{Oil\ bath\ volume}{Reactors\ chamber\ volume} = 1$$

$h = 4.66 \frac{W}{m^2 * K}$, for an insulated silicone oil bath

$A = 1.32 \frac{m^2}{reactor\ chamber}$ being the cell a rectangular parallelepiped of dimensions:

$$\begin{cases} L = 40\ cm \\ W = 40\ cm \\ H = 62.5\ cm \end{cases}$$

Being the resulting power $P_{production} = 0.49 \frac{kW}{reactor\ chamber}$, the energy consumption associated with heating is $E_{heating,CF} = 0.49 \frac{kWh}{l_{product}}$.

The energy consumption due to the stirring is calculated as follows:

$$P_{mixing} = P_0 \rho N^3 D^5$$

Where: $P_0 = power\ number\ [dimensionless]$; $N = rotation\ speed\ [s^{-1}]$; $D = diameter\ of\ the\ impeller\ [m]$; $\rho = fluid\ density\ \left[\frac{kg}{m^3}\right]$.

The energy requirements are related to the preparation of the $HAuCl_4$ solution and Na_3Cit solution for a total of $E_{mixing,CF} = 0.004 \frac{kWh}{l_{product}}$. The feeding of the CF system is composed of a set of 15 multichannel peristaltic pumps (0.1 kW) for the feed of precursor and segmenting fluid, separation and recirculation, and 12 circulation pumps for cleaning operations and waste streams (0.8 kW): $E_{pumping,CF} = 2.21\frac{kWh}{l_{product}}$.

With regard to the operational procedures, the dead times take 10% of the total production time, due to cleaning and maintenance (refer to Table 5.5). The resulting total productivity is equivalent to the reference yearly production (batch system) of 2.51 kg of AuNPs (dry weight).

Table 5.5 - Production time for the continuous flow system: operative and dead times due cleaning and maintenance.

		Time	
		h	*d*
Continuous flow production cycle		336	14
26 continuous cycles per year: each cycle covers 2 weeks and includes production, cleaning and maintenance	Net production time	302.4	12.6
	Cleaning	17.6	0.7
	Maintenance	16.1	0.7

The segmenting fluid, heptane, is separated from the synthesis fluid downstream of the growth phase and recirculated back into the reactor feed (see Figure 5.5). In order to take into account the possibility of contamination of the recycled heptane, we assumed that the heptane is kept in the system for a maximum of 24 h, and that is sent out to waste disposal while fresh heptane is fed into the system. The separation is achieved through a liquid/liquid flow separator. The heptane is immiscible with the synthesis solution at room temperature.

With regard to the cleaning phase, it is performed cyclically with heptane and water as cleaning agents. The volume of heptane flowing per cleaning cycle is 5.4 l, equivalent to 0.135 l per reactor: $\frac{\text{heptane cleaning volume}}{\text{hold up of the system}} = 5$. Afterwards, the system is washed with water (20:1 in volume with respect to heptane). The stream of heptane coming out of the cleaning is collected and disposed of as hazardous waste (the quantity of heptane disposed is around 230 kg/y) in accordance with heptane's Safety Data Sheet (SDS). It is expected that the concentration of gold nanoparticles in the waste stream is below 1 ppm, due to the fact that the production systems achieves conversion of the gold precursor close to 100%.

With regard to labour, it is expected that the production would involve a technician working full time and a system of emergency during the non-working hours for exceptional interventions. The inventory information about the CF system, provided in this section, is summarised in Table 5.6.

Table 5.6 - Inventory list for the continuous flow system: materials, energy consumption and labour.

Groups	Item	Quantity	
Chemicals	$HAuCl_4$ trihydrate	4.33	*kg*
	Trisodium citrate	19.7	
	Water	44000	
	Heptane	134.4	
Cleaning	Water	23010	*kg*
	Heptane	95.7	
Reactor equipment and service fluids	Teflon capillary	120	*m*
	Silicone oil	3880	*kg*
Peripheral equipment	Membrane separator	1	*unit*
	Pumps	27	
Energy consumption	Electricity (Heating)	21609	*kWh*
	Electricity (Mixing)	171.1	
	Electricity (Pumping)	97306	
Labour	Technicians	2920	*person*h*
Waste disposal	Water treatment	1500	m^3
	Hazardous waste	230	*kg*

5.3.2.2 Batch system

The batch production system is structured in production cycles of two days of synthesis. A production year is composed by 126 of these batch cycles (equal to a dry weight of 2.51 kg of gold nanoparticles) on the basis of 252 working days. $HAuCl_4$ and Na_3Cit solutions are fed into four parallel production lines (see Figure 5.7), each one composed of a stirred batch reactor. These two solutions are processed in the reactor with the same molar ratio adopted in the CF setup ($\frac{mol\ Na3Cit}{mol\ HAuCl4} = 6$). The resulting synthesis liquid is less diluted with respect to the CF system. The gold nanoparticles are in fact formed with a final concentration of OD5. The dilution occurs downstream of the reactors, where the final concentration of OD1 is achieved in a dilution tank. A buffer tank is placed between the reactors and the dilution tank for the regulation and equalisation of the synthesis flow. Specifically, the vessels used in the synthesis are:

- 4 double jacketed batch reactors (borosilicate) with stirring (10 l each)
- 1 jacketed buffer tank (borosilicate) with stirring (60 l)
- 1 jacketed dilution tank (borosilicate) with stirring (350 l)

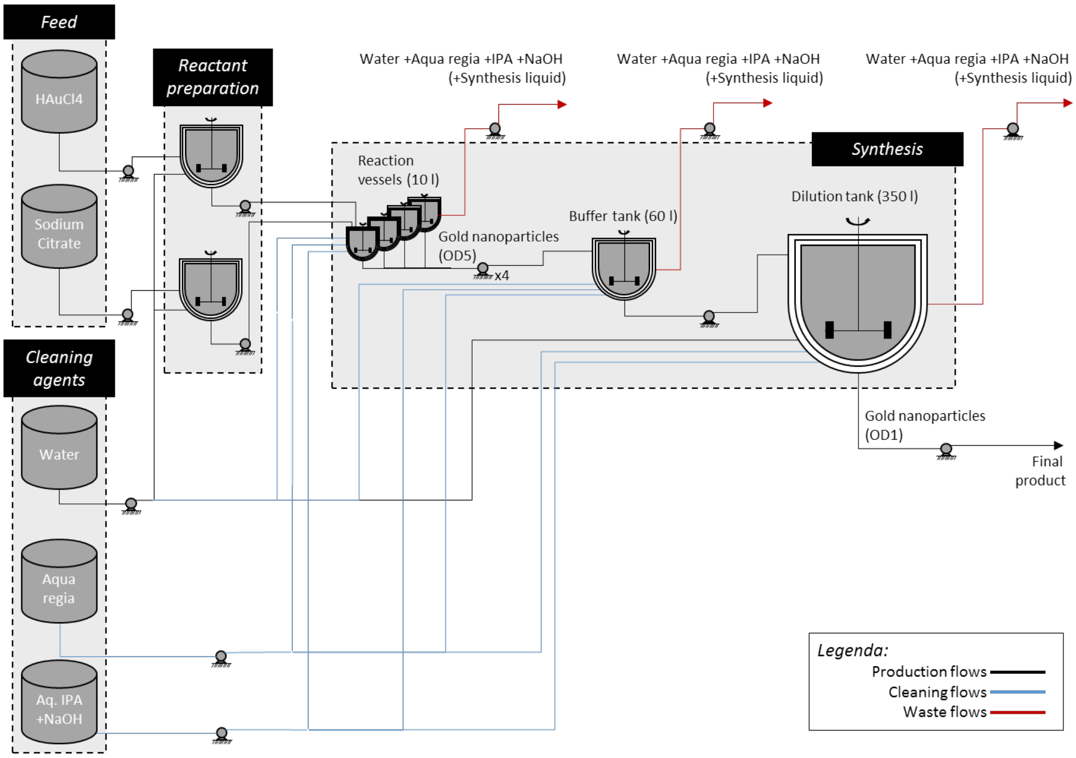


Figure 5.7 - Overview of the batch production system for AuNPs: process flow diagram.

The heating system is composed of a thermal bath using silicone oil as thermal fluid. The calculation of the energy requirements follows the same approach as showed for the CF system:

$$h = 4.66\frac{W}{m^2 * K}$$

$$A = 0.5\frac{m^2}{vessel}$$

The power requirements and the energy consumption for the ramp-up of temperature and production are:

$$P_{production} = 0.2\frac{kW}{vessel}$$

$$E_{production} = 5.96\frac{kWh}{cycle}$$

$$E_{rump\ up} = 7.42\frac{kWh}{cycle}$$

Hence, the resulting energy consumption is $E_{heating,batch} = 0.04\frac{kWh}{l_{product}}$. With regard to the mixing, the average power loss is calculated following the same procedure as in the continuous flow system (refer to section 5.3.2.1):

$$P_{mixing,batch} \sim 11\frac{W}{l}$$

The total energy duty allocated to mixing is then $E_{mixing,batch} = 0.115\frac{hWh}{l_{product}}$. A total of 12 circulation pumps (0.8 kW) for cleaning, circulation and waste stream, and 4 peristaltic pumps

(0.1 kW) for the feeding of precursors, were considered, being the total average consumption: $E_{pumping,batch} = 0.46 \frac{kWh}{l_{product}}$.

With regard to the operational procedures, a cycle of production is composed of a day of production and a day of cleaning. The cleaning procedure comprises three steps:

- Manual surface cleaning of the vessels and stirrers with aqua regia; $1.25 \frac{\mathrm{l}}{\mathrm{m}^2_{reactor\,surface}}$
- Cleaning with isopropyl alcohol (IPA) (90%) solution saturated with NaOH for neutralization; $1 \frac{l_{solution}}{l_{reactor}}$
- Washing with water; $\frac{\text{water volume}}{\text{vessel volume}} = 5$

The waste streams coming from the cleaning are sent to a collection tank and are disposed of as hazardous waste. These streams contain high quantities of aqua regia, organic solution and residues of the synthesis and are required to be disposed via incineration as per the SDS related to such compounds.

With regard to the personnel involved in the plant, the calculation of the labour followed the listed assumptions:

- A total of two technicians working full time during the production and cleaning phase
- an average of 20 h per week is required for the characterisation

The inventory information about the batch system, provided in this section, is reported in Table 5.7.

Table 5.7 - Inventory list for the batch system: materials, energy consumption and labour.

Groups	Item	Quantity	
Chemicals	$HAuCl_4$ trihydrate	4.33	*kg*
	Trisodium citrate	19.7	
	Water	44000	
Cleaning	Aqua regia	223	*kg*
	IPA	43018	
	NaOH	7596	
	Water	289575	
Reactor equipment and service fluids	J. batch (350 l)	1	*unit*
	J. batch (60 l)	1	
	Double j. batch (10 l)	4	
	Silicone oil	100	*kg*
Peripheral equipment	Pumps	16	*unit*
Energy consumption	Electricity (Heating)	1686	*kWh*
	Electricity (Mixing)	5081	
	Electricity (Pumping)	20167	
Labour	Technicians	5072	*person*h*
Waste disposal	Water treatment	1500	m^3
	Hazardous waste	340	*t*

5.4 RESULTS AND DISCUSSION

Results are organised into two sections: environmental impact assessment and cost assessment. Each section offers an analysis on the results related to the single production systems, as well as a comparative analysis.

5.4.1 ENVIRONMENTAL IMPACT ASSESSMENT

The results of the LCA are divided into three sub-sections, each one offering a different perspective on the environmental impact of the AuNPs production systems:

- Normalisation and scenario analysis

  This section contextualises the environmental impacts of the AuNPs production in the broader context of European emissions. It also provides a projection of the environmental impacts of the AuNPs production in the scenario in which gold nanoparticles are fully adopted in nano-enabled medical applications.

- Technology comparison

  The absolute environmental impacts of the batch and continuous flow production technologies are compared and discussed.

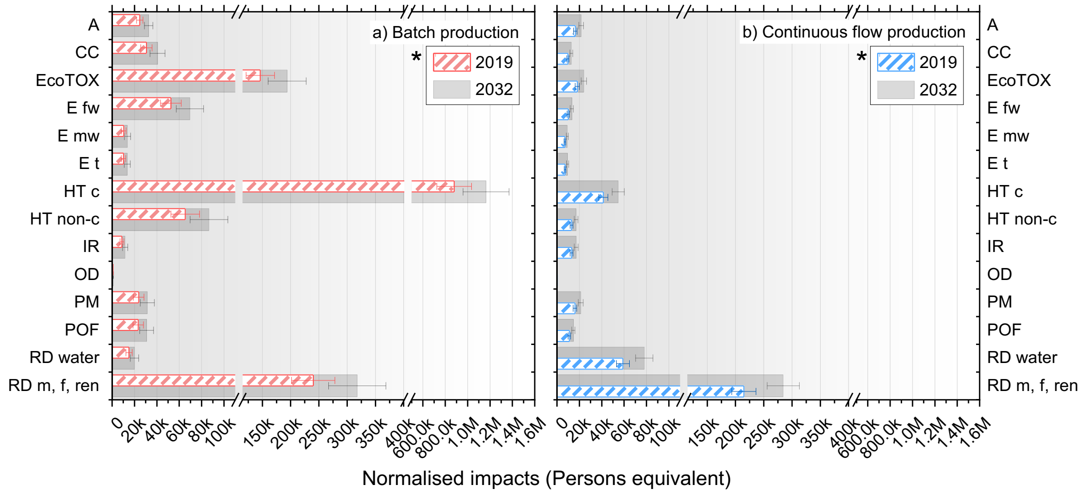
- Hotspot analysis

  A hotspot analysis is undertaken. The goal of this section is identifying the causes of the environmental impacts of the AuNPs production systems.

5.4.1.1 Normalisation and scenario analysis

Through the normalisation, the environmental impacts are expressed in “persons equivalent”. It is a way of expressing the weight of the environmental impact of the production system considered on the total environmental impact arising from a geographical region, which in this case is Europe.

The results of the normalisation are showed in Figure 5.8 for batch and CF production systems. The figure refers to the case in which gold nanoparticles are fully adopted in nano-enabled medical applications in the UK.



* The estimated demand of gold nanoparticles in 2019 is 594 kg – on the basis of the nano-enabled medical applications already on the market or that have the potential to be introduced in the market[247]. In 2032, the demand of gold nanoparticles in the UK is estimated to increase and reach 770 kg. This value is obtained on the basis of World Health Organisation's prediction of cancer cases in 2032[248,249]; tumour targeting is in fact the main medical application of AuNPs and hence the demand of AuNPs is expected to grow accordingly with cancer cases.

Figure 5.8 - Normalised LCIA results for a) batch production and b) continuous flow production: each graph refers to the scenario in which gold nanoparticles are fully adopted in nano-enabled medical applications in the UK, for two time horizons.

In the analysis, two scenarios are outlined: a present situation and a projection of the impacts in the future. With regard to the 2032 scenario, this takes into account the growth of cancer-cases estimated by the WHO; the latter could eventually reflect in an additional demand of AuNPs and consequently increased production. As mentioned in the Introduction, it is paramount to consider the potential evolution of the market in order to anticipate the consequences of a burdened production system in relation to issues such as the availability of gold resources. Evidently, by looking at Figure 5.8a, the batch production system has high environmental impacts, primarily with respect to Human Toxicity (cancer effects). In this impact category, the normalised impact is equal to nearly one million persons equivalent in 2019 and exceeds 1 M persons equivalent in 2032. As explained previously, each bar of the graphs in Figure 5.8 is obtained by dividing the environmental impact of the production system in a specific impact category by the environmental impact of all European activities; the number obtained –that is the share of the total environmental impact arising from Europe – is then multiplied by the European population. Therefore, this means that the environmental impact of the batch production system in Human Toxicity (cancer effects) in 2019 is equal to the 0.2% of the environmental impact arising from Europe in the same impact category. This percentage share may seem small, but instead is particularly high considering that: firstly, it refers only to a specific industrial field of application (gold nanoparticles for nano-medical applications); secondly, it refers only to a specific region (UK) and not to the demand of gold nanoparticles in Europe.

The first main output of the normalisation is hence that the full exploitation of gold nanoparticles in nano-enabled medical applications can have a magnitude of environmental impact of continental scale, and therefore, the production system of gold nanoparticles needs to be properly considered before its large scale-deployment. To this end, it is also worth noting that the projected environmental impact of the AuNPs production systems is expected to increase - by 33% circa in 2032 (grey bars in Figure 5.8). This additional environmental impact is a consequence of the increase of lung and neck cancer cases expected in the next years. This will therefore lead to an increase of cancer treatments, which is the main medical application of gold nanoparticles.

Figure 5.8b offers a different perspective on the same matter by reporting the environmental impact of the production of gold nanoparticles in the case in which the innovative continuous flow technology is adopted in place of the conventional batch technology. The scenario considered is the same, namely the full exploitation of gold nanoparticles applications in the UK. In this case, however, the results show that the normalised environmental impact of the CF production systems is on average lower than the batch production systems, in all the impact categories considered. For example, Resource Depletion (minerals, fossils, renewables) is the impact category showing the highest impact for the CF system; however, this impact is equal to 200k persons equivalent circa, which translates into a mere 0.04% of the total European environmental impact in the same impact category. This is circa one order of magnitude lower compared to the highest normalised impact of the batch system (0.2% in HT, cancer effects).

In light of the above, it is clear that an enhanced production technology, such as the continuous flow, could significantly reduce the emissions related to the production of gold nanoparticles. This is especially crucial when we consider the large scale-deployment of this production system that is needed for fulfilling the potential demand of gold nanoparticles. In this respect, a detailed comparison of batch and CF production technologies is reported in the following section 'Technology comparison'.

Another major output of the normalisation is that it enables a comparison of the environmental impacts across different impact categories and hence it is possible to have a criterion of selection of the impact categories of major relevance. In order to enable such selection, it is necessary to look at the shares of the total impact of batch and CF production for each impact category considered in the analysis. The total impact of a production system is the sum of the normalised impacts of all the impact categories. The total impacts of batch and CF production are respectively 1.29 M and 0.22 M persons equivalent. Consequently, the share of the total impact for each impact categories is obtained by dividing the normalised impact of a given impact category by the total impact of the production system considered. For example, the normalised impact for Human Toxicity (cancer effects) in the batch system is 0.88 M persons equivalent and hence the share of the total impact is 57%. The same procedure is followed for the rest of the impact categories and the results are reported in Table 5.8.

Table 5.8 - Share of the total impact for batch and continuous flow production for the impact categories considered in the normalisation.

Impact categories	Share of the total impact*		Relevance
	Batch	Continuous flow	
Human toxicity, cancer effects	57%	9%	HIGH
Resource depletion, mineral, fossils and renewables	16%	49%	
Ecotoxicity freshwater	10%	4%	
Human toxicity, non-cancer effects	4%	3%	MODERATE
Eutrophication freshwater	3%	2%	
Acidification	2%	4%	
Climate change	2%	2%	
Particulate matter	2%	4%	
Photochemical ozone formation, human health	2%	3%	
Resource depletion, water	1%	13%	
Eutrophication marine	1%	2%	LOW
Eutrophication terrestrial	1%	2%	
Ionizing radiation	1%	3%	
Ozone depletion	<1%		

*Total impact is the sum of the normalised impact of all the impact categories and is equal to: 1.29 M persons equivalent for the batch system and 0.88 M persons for the continuous flow system

As it emerges from Table 5.8, the highest shares are those related to Human Toxicity (cancer effects), Ecotoxicity and Resource depletion (minerals, fossils and renewables) whilst Eutrophication marine water and terrestrial, Ozone depletion and Ionising radiation contribute only marginally to the overall impact of the system. Therefore, these impact categories are excluded from the following analyses ('Technology comparison' and 'Hotspot analysis') with the aim of narrowing down the scope of such analyses to the most critical environmental consequences. It is worth noting that the order of relevance of the impact categories listed in Table 5.8 changes significantly for the CF system compared to the batch system. For example, Human toxicity (cancer effects) and Resource depletion (minerals, fossils and renewable) showed the highest contribution (57% and 16% respectively) in the batch production system, while the result is inverted for the CF system. On the other hand, the impact related to Resource Depletion (mineral, fossils and renewables) takes 49% of the total impact of the CF production. This share is increased with respect to the batch system (16%) and hence this may suggest an increase of the impact; on the contrary the impact is reduced. The reason behind this lies that the total environmental impact of the continuous flow system is lower than the batch system: 0.22 M and 1.29 M persons equivalent respectively, as reported before.

In order to capture the factors that make the continuous flow system have a reduced environmental impact compared to the batch system, it is necessary to complement the results of the normalisation analysis with the direct comparison of the absolute environmental impacts of the two production systems. Such comparison is offered in the next section and it shows that the different shares of the total impact highlighted in Table 5.8 are generally attributable to drastic reductions of the environmental impacts of the CF production with respect to the batch production in certain impact categories.

5.4.1.2 Technology comparison

The comparison of the absolute environmental impacts of the batch and continuous flow production technologies is shown in Figure 5.9: the graph refers to 1 l of product obtained from the yearly production of gold nanoparticles. In this section the environmental impacts are expressed through absolute units instead of the normalised unit (persons equivalent) adopted in the normalisation. Therefore, it is no longer possible to compare the environmental impacts across different impact categories and the columns in Figure 5.9 must be compared only within the same impact category. The columns are equalised for sake of readability: every columns' value needs to be multiplied by the factor reported on the inside top of the graph's area. The boxes report the percentage change of the environmental impact of the CF production with respect to the batch production.

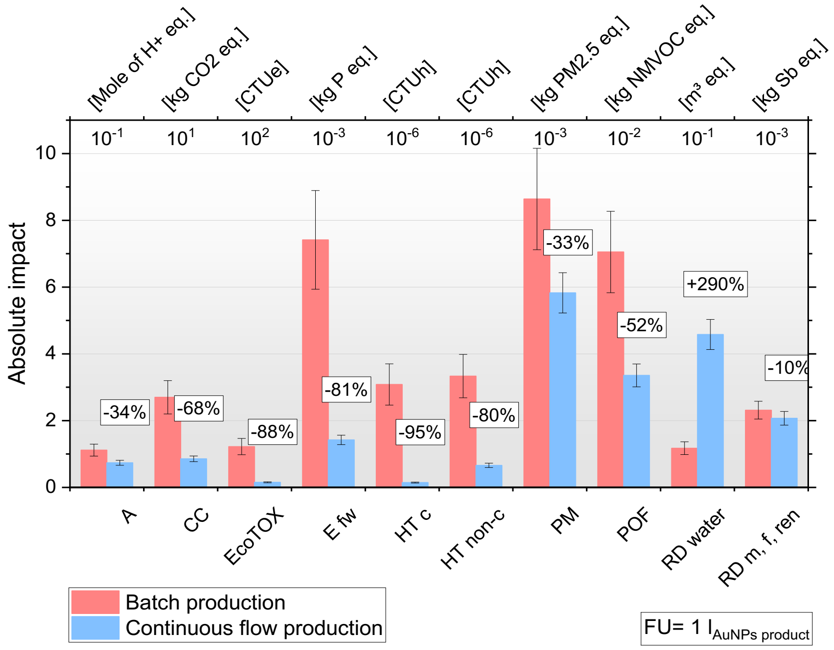


Figure 5.9 - Absolute LCIA results and comparison: absolute impacts per 1 l of AuNPs product for batch and continuous flow system.

The continuous flow production achieves significantly lower environmental impacts compared to the batch production in every impact category with the exception of Resource Depletion (water). The percentage reduction of environmental impact span from -10% (in RD minerals, fossils, renewables) to -95% (in HT cancer effects) with the major savings being in the impact categories: Climate Change, Ecotoxicity of freshwater, Eutrophication of freshwater, Human Toxicity (cancer and non-cancer effects) and Photochemical Ozone Formation.

The relative importance of the percentage changes shown in Figure 5.9 is appreciable relating these percentage changes to the values reported in Table 5.8 that highlights the relative weight of each impact category with respect to the total impact of the production system. For example, Figure 5.9 may give the impression that Resource Depletion (Water) is the category with the most relevant impact change when comparing batch to CF production. However, this change (+290%) must be looked at also considering the normalised analysis (Table 5.8); this showed that the impact of Resource Depletion (Water) is marginal when compared to the total impact of the batch production (1% of the total environmental impact). Therefore, the percentage change of the impact in Resource Depletion (water), in Figure 5.9, is negligible when compared to the percentage change in those impact categories that have a higher share of the total impact of the production systems. These impact categories are highlighted in Table 5.8 and are, in order of importance, Human Toxicity (cancer effects), Resource depletion (mineral, fossils and renewables) and Ecotoxicity of freshwater.

It is worth noting that the CF production showed a reduction of the environmental impact in all of these impact categories compared to the batch production. Specifically, the impacts of the CF production are reduced by 95% in Human Toxicity (cancer effects), by 88% in Ecotoxicity of freshwater and by 10% in Resource Depletion (mineral, fossils and renewables). The latter is the lowest percentage reduction compared to other impact categories. This suggests that the primary causes of the impact in RD (mineral, fossils and renewables) might be elements in common between the batch and CF systems, such as the synthesis method. In fact, Resource Depletion (mineral, fossils and renewables) takes into account the depletion of gold, which is used as the main raw material for the production of the gold precursor ($HAuCl_4$) for both the batch and the continuous flow production systems. More insight on the causes of the environmental impact of the two systems are presented in the next section through the hotspot analysis.

5.4.1.3 Hotspot analysis

The previous sections profile that the batch and continuous flow production systems have a radically different environmental impact. In this section, the causes of the different environmental impacts are identified through a hotspot analysis. The latter was performed by following two approaches:

- By groups (Figure 5.10);

  the environmental impacts are sorted on the basis of the inventory group that caused the impact. These groups are the same groups defined during the Life Cycle Inventory, namely, chemicals, energy consumption, reactor equipment and service fluids, cleaning and waste disposal. Through this approach, it is possible to localise the generic source of the impact in the production system

- by activity (Figure 5.11);

  the environmental impacts are sorted on the basis of the activity that caused the impact (i.e. incineration, sodium citrate production, etc.). It is worth remembering that each activity belongs to a specific group (see Table 5.9); thus, the sum of all the environmental impacts or costs of the activities in a given group is equal to the environmental impact of that group. For example, the environmental impact of the group 'Chemicals' is the sum of the environmental impacts of the activities belonging to 'Chemicals', namely: $HAuCl_4$ production, sodium citrate production, heptane production and water use.

Table 5.9 - List of the inventorial groups and related activities.

Groups	**Activities***
Chemicals	$HAuCl_4$ trihydrate production
	Sodium citrate production
	Water use
	(CF) Heptane
Cleaning	(B) Aqua regia production
	(B) IPA production
	(B) NaOH production
	(CF) Heptane
	Water use
Reactor equipment and service fluids	(B) Borosilicate reactor manufacturing
	(CF) Teflon capillaries manufacturing
	Silicone oil production
Energy consumption	Electricity production, heating
	Electricity production, mixing
	Electricity production, pumping
Waste disposal	Wastewater treatment
	(B) Hazardous treatment incineration

*the activities that are specific only to a production system are preceded by brackets: (B) batch production system, (CF) continuous flow production system

This approach to the hotspot analysis brings out a higher level of information than the hotspot analysis sorted by groups, and hence it is possible to trace the primary causes of the environmental impacts.

The results of the hotspot analysis, sorted by groups, are reported in Figure 5.10.

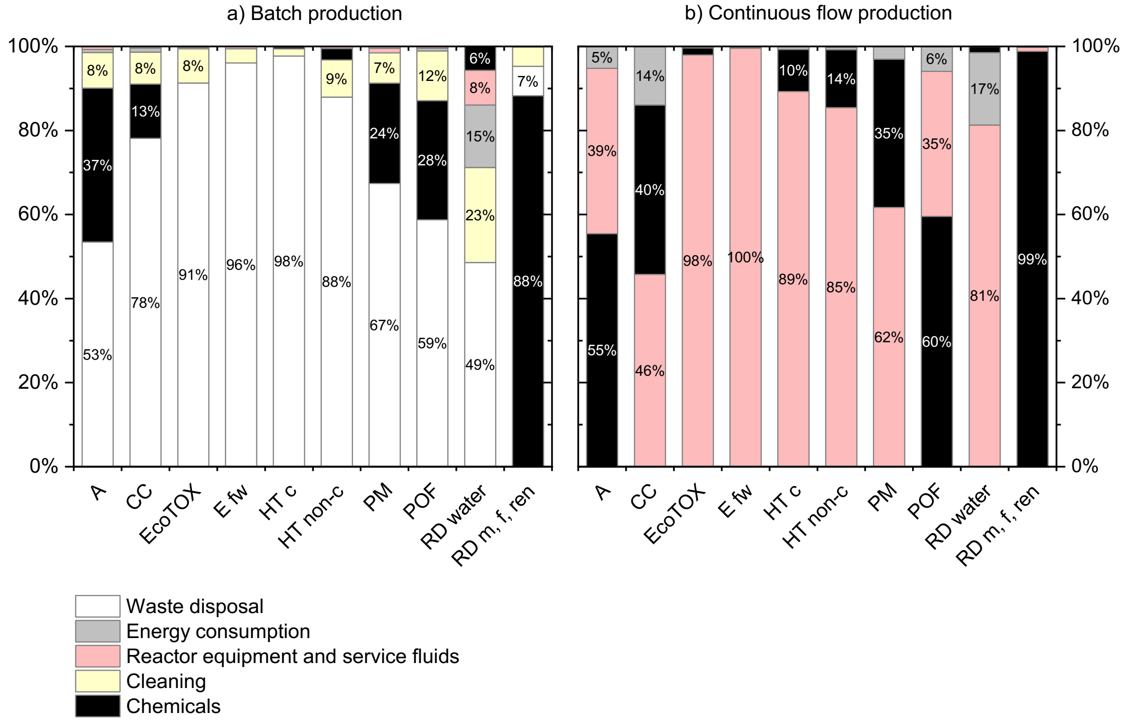


Figure 5.10 - Hotspot analysis (sorted by group) for: a) Batch system, b) Continuous flow system.

On the one hand, the main contributors to the environmental impact of the batch system (Figure 5.10a) are waste disposal, chemicals and cleaning. Energy consumption and reactor equipment and service fluids contribute only marginally to the overall environmental impact. Their contributions is negligible (<2% of the total impact of the batch production) in every impact category exception made for Resource Depletion (water) but, as seen before, the latter is an impact category of minor relevance (Table 5.8).

On the other hand, the largest share of the environmental impact of the CF system (Figure 5.10b) is associated with reactor equipment and service fluids, chemicals and, in minor part, energy consumption. Waste disposal and cleaning contribute to less than 1% of the total the total impact of the CF production in all the impact categories.

By cross comparing the results of the hotspot analysis with the absolute impacts reported in the previous section, it is clear that the reduced environmental impact of the CF system compared to the batch system is mainly attributable to the differences in the cleaning procedures and treatment of wastes. To capture this, it is necessary to consider three factors:

- the largest share of the total environmental impact of the batch production is associated with the impact categories of Human Toxicity (cancer effects), Resource depletion (mineral, fossils and renewables) and Ecotoxicity of freshwater, as emerged from the normalisation in Table 5.8.

- In these impact categories, the continuous flow production showed major percentage reductions of the impact (Figure 5.9): respectively, -95%, -10% and -88% compared to the batch production.
- The hotspot analysis showed that, in these impact categories, the main differences between batch and CF production are due to waste disposal and cleaning. Specifically, this is shown in Figure 5.10a (HT c., EcoTOX and RD m., f., ren.) where waste disposal and cleaning are the "hotspots" of the batch production whilst they are practically untraceable in the CF system, see Figure 5.10b.

The second part of the hotspot analysis investigates into the causes of the environmental impact in more depth by looking at the single activities -composing the life cycle of the production systems- responsible for the impacts. Each activity belongs to a specific group (see Table 5.9); thus, the sum of all the environmental impacts or costs of the activities in a given group is equal to the environmental impact of that group. For simplicity, the group to which each activity belongs is indicated after the name of the activity, in brackets (i.e $HAuCl_4$ production (Chemicals), electricity production, mixing (Energy consumption), etc.).

The results of the hotspot analysis, sorted by activity, is reported in Figure 5.11.

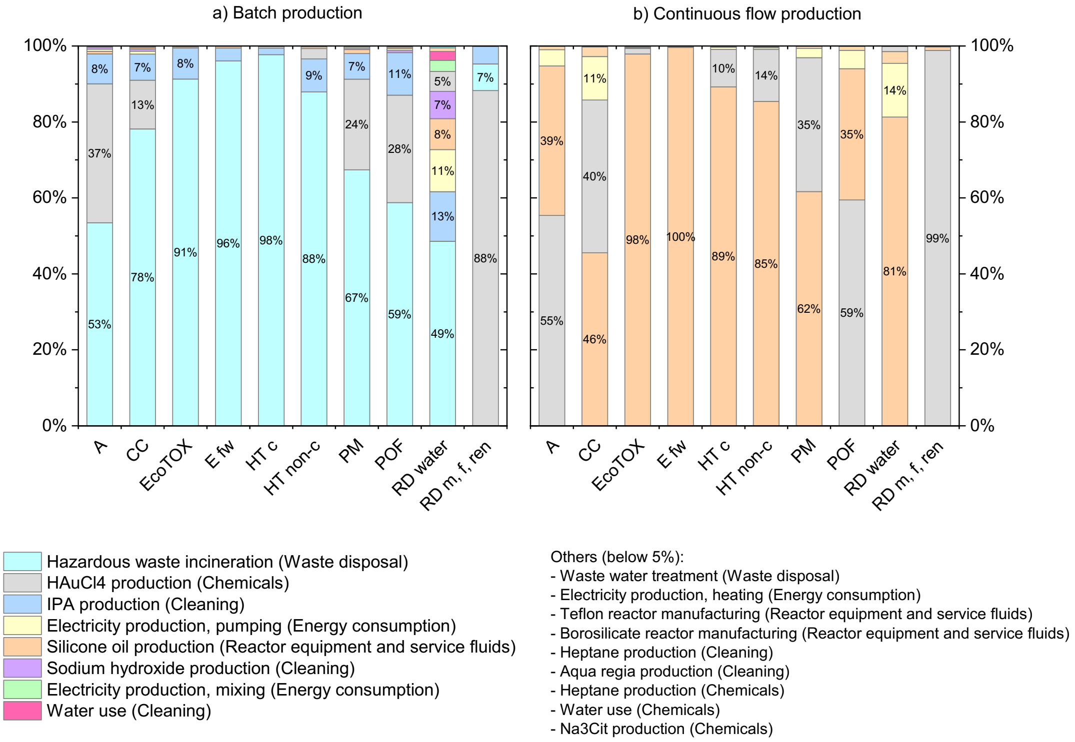


Figure 5.11 - Hotspot analysis (sorted by activity) for: a) Batch system, b) Continuous flow system.

The activities that take most of the share of the environmental impact of the production of gold nanoparticles are:

- Hazardous waste incineration (Waste disposal), $HAuCl_4$ production (Chemicals), IPA production (Cleaning) and Sodium hydroxide production (Cleaning) for the batch system (Figure 5.11a)
- Silicon oil production (Reactor equipment and service fluids), $HAuCl_4$ production (Chemicals) and Electricity production, pumping (Energy consumption) for the continuous flow production (Figure 5.11b)

It is worth noting that each one of these activities is the main cause for the environmental impact of the group to which they belong (indicated in brackets). This is appreciated by looking at the percentage share of these activities in Figure 5.11 in comparison with the percentage share of the related groups in Figure 5.10: these activities take nearly the whole share of the environmental impact of the group to which they belong.

The hotspot analysis is particularly useful for identifying the causes of the environmental impact in those impact categories that, through the normalisation, were found to be the most relevant for the LCA: Human Toxicity (cancer effects), Resource depletion (mineral, fossils and renewables) and Ecotoxicity of freshwater. It must be stressed that the total environmental impact of the two production systems is coming for the major part from these impact categories. Therefore, the activities that contribute the most to the environmental impact in these impact categories are the mere primary causes of the total environmental impact of the two systems: hazardous waste incineration and production of $HAuCl_4$.

It must be also noted that the CF system showed a significant percentage reduction of the environmental impact compared to the batch system in each of these highly relevant impact categories. This must be taken into account when looking at the results of the hotpots analysis of the continuous flow system (Figure 5.11b). For example, the fact that silicone oil production is barely present in Figure 5.11a (batch hotspot) whilst being a predominant contributor in Figure 5.11b (CF hotspot), does not indicate an increase of the environmental impact of the production of silicone oil in the CF system. This effect is the result of the absence or strong reduction, in the life cycle of the CF system, of those ‘high impacting’ activities that are present in the life cycle of the batch production, namely, hazardous waste disposal, IPA production and sodium hydroxide production. Therefore, some ‘low impacting’ activities, such as silicone oil production, that were out of the radar of the hotspot analysis of the batch system, emerge in the hotspot of the CF system: their relative share of the impact increases compared to the batch system even though their absolute environmental impact does not change.

In consequence of the previous considerations, the rest of the activities investigated through the hotspot analysis have negligible effects on the total environmental impact of the production systems. These ‘low impacting’ activities are listed in the legend of Figure 5.11 but are not easily traceable in the graphs as their share of the environmental impact was found to be below 5% in every impact category.

Lastly, further insight is offered with regards to the two activities that emerged from the hotspot analysis as the major causes to the environmental impact of the production of gold nanoparticles, namely hazardous waste incineration and production of $HAuCl_4$.

- Hazardous waste incineration

  Hazardous waste incineration is the main contributor to the life cycle emissions of the batch system: it takes 96% and 98% of the environmental impact in Human Toxicity (cancer effects) and Ecotoxicity of freshwater (Figure 5.11a). The wastes of the batch system are composed for the major part by the high volumes of aggressive cleaning agents arising from the cleaning procedures. The cleaning of the batch reactors requires, in fact, abundant quantities of IPA, aqua regia and sodium hydroxide that are disposed after the cleaning phase. The resulting waste stream has to be treated as hazardous waste, according to the SDS of these compounds, via incineration. The environmental impact of the incineration is mainly attributable to emissions of compounds that contain sulphur, nitrogen, halogens (such as chlorine), and toxic metals. These emissions are of primary concern, owing to their potential effects on human health and the ecosystem.

  On the other side, the CF system produces primarily a non-hazardous waste stream and hence has a much lower environmental impact associated with waste disposal. The wastes of the CF production are in fact principally composed by mild cleaning agents used in the cleaning procedures (only small quantities of heptane are used, around 230 kg/y). Consequently, the impact of the hazardous waste incineration is negligible: virtually the entire waste stream is processed into wastewater treatment facilities whose resulting impact takes less than 1% of the total environmental impact of the CF system in all the impact categories considered in the analysis (see Figure 5.11b).
- $HAuCl_4$ production

  $HAuCl_4$ is used as the gold precursor in the synthesis of gold nanoparticles. Its production strongly affects the environmental impact of the batch and continuous flow production systems.

  The high environmental impact of the production of $HAuCl_4$ is caused predominantly by the extraction of the gold needed for its production. The gold extraction activities are, in fact, highly energy-demanding and resource consuming, and have a high impact on acidification, climate change and resource depletion. The standard method of gold extraction worldwide is the cyanide method[279]. The mining, comminution (crushing and grinding) and cyanidation stages make the greatest contribution to the environmental impact of this process, with electricity being responsible for just over half of the greenhouse gas footprint[280]. It is worth noting that the environmental footprint of the extraction of gold is expected to increase in the next years in consequence of falling gold ore grades.

With regard to how this affects the comparison of the two production technologies, it is firstly necessary to recall that the LCA emphasized the lower environmental impact of the continuous flow system, compared to the batch system, in nearly all the impact categories considered. Among these, the percentage reduction of the impact in Resource Depletion (mineral, fossil, renewables) was the lowest reduction of impact achieved by the continuous flow production (-10%, Figure 5.9). This impact category emerged from the hotspot analysis as strongly dependent on the environmental impact of $HAuCl_4$ production (between 88% and 99%, Figure 5.11). However, it is impossible to reduce the environmental impact associated with $HAuCl_4$, and hence further reduce the total environmental impact of the CF system, without either changing the synthesis method or the source of gold as its use is a direct consequence of the synthesis method.

To this end, second-hand gold could theoretically be used to manufacture $HAuCl_4$ and consequently reduce the depletion of gold. It has been estimated that about 15% of all gold ever mined was used in dissipative industrial applications or is unaccounted for or unrecoverable, leaving about 85% (between 133,000 and 153,000 t) still in use and available for recycling[281]. However, the use of recycled gold would imply a redistribution of these gold stocks, today distributed in major part in the investment and jewellery sector. Therefore, this would eventually lead to increase the gold demand in those sectors deprived of the gold resource in consequence of the redistribution; thus, resource depletion would be only shifted and not reduced. The last viable option could finally be the recycling of gold nanoparticles products at the end of their cycle of use but the feasibility of this option needs to be further investigated[282].

5.4.2 COST ASSESSMENT

Figure 5.12 reports the capital and operating expenses for the batch and continuous flow systems.

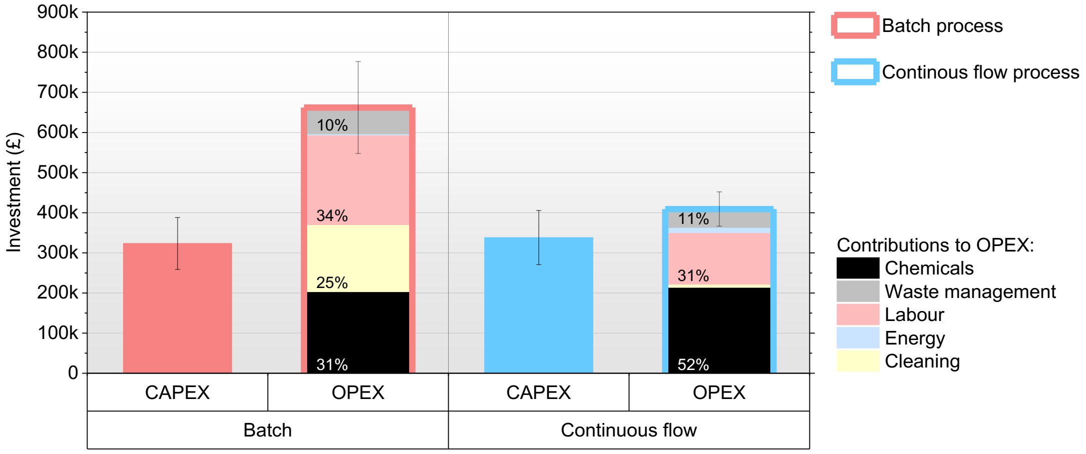


Figure 5.12 - Comparison of operating expenses (OPEX) with relative contributions, and capital expenses (CAPEX) for batch and continuous flow process.

In the CF system, the operating expenses are around 38% lower than the batch production. The main contributors to this significant reduction are the costs associated with cleaning, waste disposal and labour. The cost of the cleaning and waste disposal are closely connected as the waste arising from both production systems is mainly composed of the cleaning agents used up in the synthesis. In the batch system, the sum of the costs associated with cleaning and waste disposal is 4.3 times higher than the CF system. Aqua regia, IPA and NaOH are used in large quantities during the cleaning procedures of the batch system and they are disposed as hazardous wastes. In the continuous flow system, the cleaning is milder and involves water and small volumes of heptane, and the associated cost of disposal is negligible compared to the overall production cost. With regard to the labour cost, this is a major contributor with around 32% of OPEX in both the systems. The easiness of the operations, maintenance and cleaning of the CF system translate into less labour and hence less labour cost (42% lower than the batch system): the production requires only a technician working full time. Furthermore, the cost of chemicals is virtually identical in the two production systems (black bars in Figure 5.12); the recipe used for the synthesis in the two systems is in fact the same, except for the heptane, used in the CF system as a segmenting fluid. The additional cost of heptane, however, does not impact heavily on the operating costs of the CF system, as it is recirculated for the major part. With regard to the energy cost, energy consumption is slightly higher in the CF system. However, the associated cost is relatively low, less than 5% of the OPEX in the CF system, and hence contribute only marginally to increasing the production cost.

Figure 5.12 provides a summary of the capital expenses for the batch and CF systems. CAPEX has a similar impact on the economics of both production systems, being respectively around £323 k for the batch system and £338 k for the CF system. The difference is marginal; thus, adopting the CF system in place of the batch system does not have a tangible effect on the capital expenditure. On the other hand, the similar CAPEX but a notably lower OPEX, contribute to reduce the overall expenditures compared to the batch system. This translates into a reduced payback period in the CF system, as outlined in Figure 5.13.

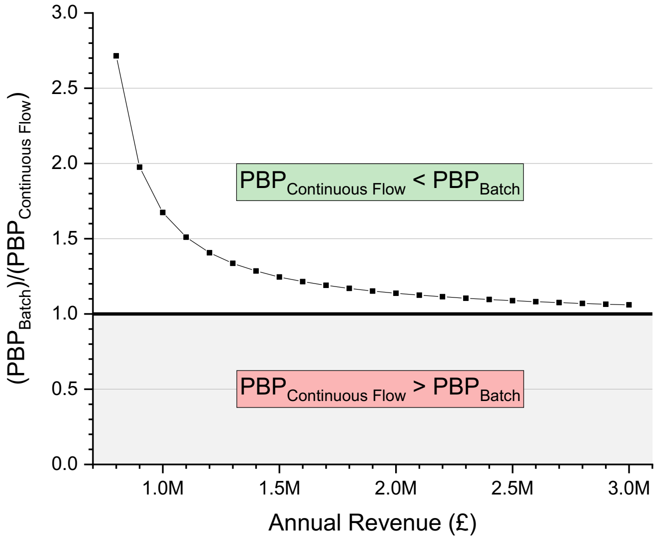


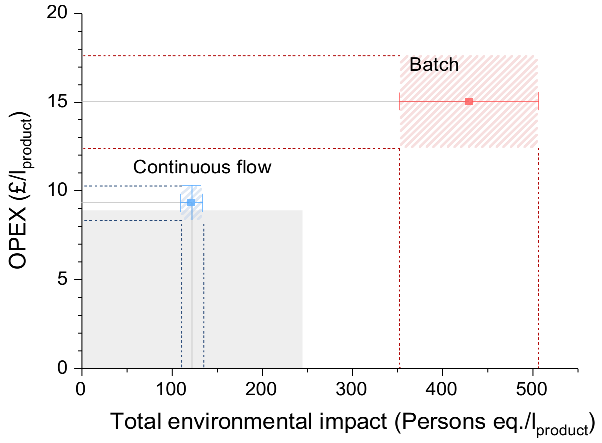
Figure 5.13 - Comparison of the payback period (PBP) for batch and continuous flow system under variable annual revenue.

The PBP of the CF system is in fact shorter than the PBP of the batch system across the whole spectrum of annual revenues. The ratio of PBP_{Batch} to $PBP_{Continuous\ flow}$ decreases with higher annual revenues as a result of a relatively high operating expenses of the two production systems compared to capital expenses. On the whole, the reduction of OPEX is identified in the cost assessment as the main business driver for the CF system. The latter emerges as a financially robust system, having a shorter payback period than the batch system, and hence being more attractive to investments.

5.5 CONCLUSIONS

In this chapter a prospective life cycle assessment and cost assessment on the production of gold nanoparticles was reported. The life cycles of two production technologies were compared, a conventional batch production, used as reference, and an emerging production technology based on milli-continuous flow. Notwithstanding the relative low maturity of the technology, the intensive efforts put in the compilation of the LCI - through the integration of direct data with indirect data stemming from the scale up/out analysis – allowed to reduce the uncertainties of the results and also expand the outcome of the assessment to economic considerations.

A major trend is clearly visible. Significant advantages can be gained from the adoption of the CF technology in place of the conventional batch technology, both economically and in terms of environmental performances (summary in Figure 5.14).



	Total environmental impact	Operating expenses (OPEX)
Production system	*Persons eq./$l_{product}$*	*£/$l_{product}$*
Batch	430 ± 77	£15.0 ± £2.6
Continuous flow	123 ± 12	£9.3 ± £1.0

Figure 5.14 - Summary of the results: comparison of operating expenses and total environmental impact of batch and continuous flow production of AuNPs.

With regard to the cost assessment, the high detail of inventorial information enabled the evaluation of both capital and operational expenditure. To this end, the cost assessment revealed that the benefits of adopting the CF system consist of a notably lower OPEX (-38%) and a shorter payback period. In the CF system, the lower OPEX stems from milder cleaning procedures and from the reduction of hazardous wastes produced (-32% in mass). Also, less labour is required compared to the batch system, and this translate into reduced expenses in this respect (-42%), thanks also to a more automated process that enables an online control system and involves no manual cleaning operations.

In terms of environmental performances, a number of drawbacks come to light from the LCA of the batch production system, namely, the production of aggressive compounds used intensively as cleaning agents, and the necessity of resorting to incineration to treat the high volumes of hazardous wastes produced in the synthesis. These factors translate into a high environmental impact that primarily concerns the impact categories of Human Toxicity (cancer effects), Ecotoxicity of freshwater and Resource Depletion (minerals, fossil, renewables); these impact categories emerge from the normalisation analysis as the major contributors to the total impact of the batch production, accounting for ca. 83% of the total impact. Furthermore, the scenario analysis highlights that, in the scenario in which gold nanoparticles are fully adopted for nano-enabled medical applications in the UK, the large-scale deployment of the conventional batch production technology would be unfavourable compared to the CF production. This is primarily evident with regard to Human Toxicity (cancer effects), Ecotoxicity of freshwater and Resource Depletion (minerals, fossil, renewables), in which the CF production system has an environmental impact respectively 95%, 88%, and 10% lower than the batch system. This significant reduction mainly springs from low volumes of hazardous waste generated during the synthesis, as shown in the hotspot analysis. A special remark should be made for the drop of carcinogenic emissions in the CF production. This is particularly relevant as gold nanoparticles are a product that has the majority of its medical applications in tumour targeting 75%[247]; thus, this severe reduction of the impact avoids the paradox of having a production system that contributes to an increase in cancer cases and hence hampers the effectiveness of its product.

Amongst the chemicals used in the synthesis of gold nanoparticles, the gold precursor ($HAuCl_4$) is the highest contributor to the environmental impact. Its production strongly hinges on gold extraction activities that have the principal consequence of aggravating the depletion of gold resources; moreover, the impact is expected to further increase in the next years as a consequence of falling ore grades. Unfortunately, mitigating the impact of $HAuCl_4$, is not an easy task. Second-hand gold could theoretically be used to manufacture this gold precursor. However, the use of recycled gold would imply a redistribution of gold resources. The redistribution of gold resources would eventually lead to an increase of gold demand in the sector deprived of its resource; thus, resource depletion would be shifted and not reduced. A potential solution might be the recycling of gold nanoparticles after their use, but the feasibility of this option needs further investigation[282].

Finally, it is worth noting that nano-enabled medical applications are growing significantly, and we envisage that gold nanoparticles will be complemented by alternative nano-products. To this end, a number alternatives have been produced, such as selenides and oxides of Pt and Bi[283], Gd[284] and Fe[285], but have not been subject yet to the same level of scrutiny as gold nanoparticles.

On the whole, the findings of this study highlight the importance of the assessments of emerging technologies and put in evidence the valuable information that can be obtained since the early stages of their development. This type of assessment proved in fact capable of providing insights on their optimisation and on the future consequences of their implementation; thus, this can be used for the screening and the selection of these technologies along process conditions and potential raw materials.

In the next chapter, the scope of the analysis shifts to an industrial R&D environment and takes another step forward in the technological stage of the target system: a production system at mini-pilot scale. The analysis will shed some light on the effect of different production scales on the projection of environmental impacts and costs. The case study is of particular interest as the assessment originated from a collaborative partnership with the company directly working on the technology development of the system under analysis.

6 CASE III – RUFINAMIDE PRODUCTION

The content of this Chapter was published in the Journal of Advanced Manufacturing and Processing, including a supporting information document containing the inventory data of the work:

Grimaldi, F., Leon Izeppi, G., Kirschneck, D., Lettieri, P., Escribà-Gelonch, M., Hessel, V., 2020. Life cycle assessment and cost evaluation of emerging technologies at early stages: The case of continuous flow synthesis of Rufinamide.

6.1 CHAPTER SUMMARY

The previous chapter has evidenced the importance of having a robust LCI when forecasting environmental impacts and costs of a process that is at the early stages of the process development. In fact, the higher maturity of the novel production system of gold nanoparticles (TRL 4) has enabled a plethora of environmental and economic considerations that was not possible to derive in the case of the less mature (TRL 3) formate production system assessed in Chapter 4.

In this chapter, an additional step is taken in the dimension scale of the target system. The emerging technology under analysis is a continuous flow system currently being tested at a mini-pilot scale (TRL 4.5) for the production of a pharma product. The setup originates from the industrial R&D of Microinnova GmbH, a company set in Austria that took part to a collaborative partnership with UCL under the EU project 'COSMIC': full access to the development data of the innovative production system was granted. This rendered possible to assess the latter at its current mini-pilot scale (TRL 4.5) as well as at the precursor lab scale (TRL 4), thus allowing considerations on the effect of the scale-up on the projection of environmental and economic performances of the continuous flow system.

To this end, the development of continuous flow technologies in the pharma and fine chemical industries is a process intensification step of primary importance towards the manufacturing of high-quality products, while reducing the environmental impact and cost of production. These can be measured through LCA and cost evaluation: as discussed in Chapter 3, such assessments need to be performed at different stages of the process development when applied to emerging technologies, in order to limit the uncertainties arising from the scale-up, and hence providing high-fidelity projections of environmental impacts and costs at larger scales. The output of the assessment can in fact vary significantly depending on the maturity of the technology and this translates into having different results at commercial scale compared to early estimations. Therefore, in this study we perform an assessment at two different scales of production, lab and mini-pilot scale, with the aim of quantifying the uncertainties of the assessment related to the scale-up, identifying the hotspots of the system, and hence providing guidelines for the further steps of process development. It is the first time that the synthesis of Rufinamide is evaluated at this scale.

The results show that low yields in the cycloaddition drastically affect the waste management and the production of precursors, and hence increases environmental impacts and cost of production. This calls for the need of prioritizing the optimization of this synthesis step in order to deploy a green and economically competitive production technology.

6.2 INTRODUCTION

In Section 1.1.3, several benefits of process intensification were evidenced regarding process efficiency, the use of resources and therefore sustainability[20,22–24]. In the case of pharma and fine chemical industries, continuous flow (CF) technologies[25–29] are considered good examples of process intensification, which are able to deliver high-quality products. These emerging technologies, however, are seldom used in industry because they are often not attractive to management at large scales due to economic or environmental reasons. Not all processes reach in fact commercial scale, and this translates into loss of human and capital resources. Furthermore, their development can be costly, time consuming and involve long procedures for their implementation[35].

In this context, the application of LCA methodology discussed in Chapter 3 offers the chance to quantify in an anticipatory fashion the environmental and economic performance of such emerging technologies. As outlined in the previous sections of the Thesis, this type of assessment can provide a faithful rendering of the environmental impact[36] and costs throughout the process development of an emerging technology[37] (Figure 3.1). With regard to the present study, the main objectives are to quantify the uncertainty and variability of the results depending on the scale[38], and identify the ‘hotspots’ of the system on which focus the subsequent phases of the development.

To this end, in this study we report the environmental impact and cost assessment of an intensified production technology that is still at the early stages of development: the CF synthesis of Rufinamide[286–288], an anticonvulsant drug consumed worldwide for the treatment of epilepsy[289]. The latter is assessed at different scales, a lab scale and a mini-pilot scale (productivity of 7g/h and 47 g/h respectively) in order to understand the effect of the scale-up on the environment and the costs. The low maturity of this CF system is taken into account by identifying the parameters of the synthesis (e.g operative conditions) that generate uncertainties in the results. These uncertainties are quantified by means of hotspot analysis and scenario analysis. All together, these provide a more accurate projection of the environmental impacts and costs of the system at larger scales. It is worth noting that the scale of production of pharmaceuticals is relatively low compared to that of bulk chemicals, with the average mass of pharmaceuticals produced in a single plant being 10-10^3 tonnes/year and 10^4-10^6 tonnes/year for bulk chemicals[290]. Notwithstanding this, the mass of waste generated per mass of product (i.e. E factor[291]) has been estimated to be 25->100 [290] (>200, according to other sources[292]) for pharmaceuticals, opposed to that of bulk chemicals having a E factor of <1-5[290]. This is partly a reflection of the increasing complexity of pharma products, necessitating multistep batch syntheses and large volumes of solvents[290]. Furthermore, the research for new pharmaceuticals involves intensive R&D activities at lab scale and pilot scale with substantial resources allocated[293]. Therefore, the production of pharma products can have a large environmental footprint, in spite of contained volumes of product generated. This call for the need of assessments being able to capture the potential impact of a production process from the early stages of its development and render the latter more efficient.

It is the first time that LCA is undertaken on the production of Rufinamide at a pilot scale. To date, LCA has been performed on the CF production of Rufinamide only at lab scale[294]; this study analyzed the environmental profile of different Rufinamide synthesis pathways and reported a comparison of batch and CF routes to 2,6-difluorobenzyl azide (Rufinamide precursor).

No evaluation of the consequences of the scale-up of this technology has been published yet, and more generally, only few LCA studies have been published in the literature on pilot scale productions[135,295]. To this end, the present study fills this gap by evaluating the effect of the scale-up of the CF synthesis of Rufinamide on environmental impacts and costs. As mentioned before, this is a critical aspect in the process development, and this assessment provides guidelines for the further steps of the process development, rendering the latter more efficient, less costly and preventing waste of resources.

With regard to the economic analysis, a preliminary evaluation of the CF synthesis of Rufinamide has been performed by Escriba et. al[288]. In the latter, the payback period (PBP) and cumulative cash flow (CCF) were used as main indicators. The analysis looked at the impact of the cost of the raw materials used in the process, the number of operators needed for the operation of the plant, and the capital investment. However, in this analysis the effect of variable yield of the synthesis was not evaluated thoroughly. In the present work, the latter is fully analyzed by considering the potential variation of the synthesis yield in the next steps of the process development, and how this will affect PBP and CCF.

The study is structured as follows:

- Materials and Methods

  The CF synthesis of Rufinamide is described and the assessment methodology is presented.

- Results and Discussion

  This section reports the results of the LCA and cost assessment. These includes a scenario analysis, hotspot analysis and comparative analysis.
- Conclusions

6.3 MATERIALS AND METHODS

6.3.1 FRAMEWORK

This section is divided into three parts, on the basis of the framework presented in Section 3.2. Firstly, the subject of the assessment, the CF synthesis of Rufinamide, is described in 'System Definition'. This offers an overview of the synthesis method, a description of the operative conditions adopted at different scales, and the process parameters on which the environmental impact and cost assessment focus on. Lastly, 'Environmental impact assessment' and 'Cost assessment' report a description of the methodology adopted and the calculation of the results.

6.3.1.1 System definition

In this phase the process flow diagrams (PFD), material and energy flows are defined for the production systems under analysis. The full set of operations involved in a full-scale PFD is taken into account, namely, the precursors' preparation, pumping, synthesis, heating and mixing, cleaning, separation, recycling, waste disposal.

The resulting information is organised in the Life Cycle Inventory (LCI).

6.3.1.2 Assessment phase

- Life Cycle Inventory

  At the basis of the LCI there is the definition of the Functional Unit (FU), which quantifies the function of the product under study and provides a reference to which input and output data are normalized; in this study the selected FU is 1 kg of

Rufinamide. The data for the LCI are quantified for each unit process included into the defined system boundaries (Figure 6.1).

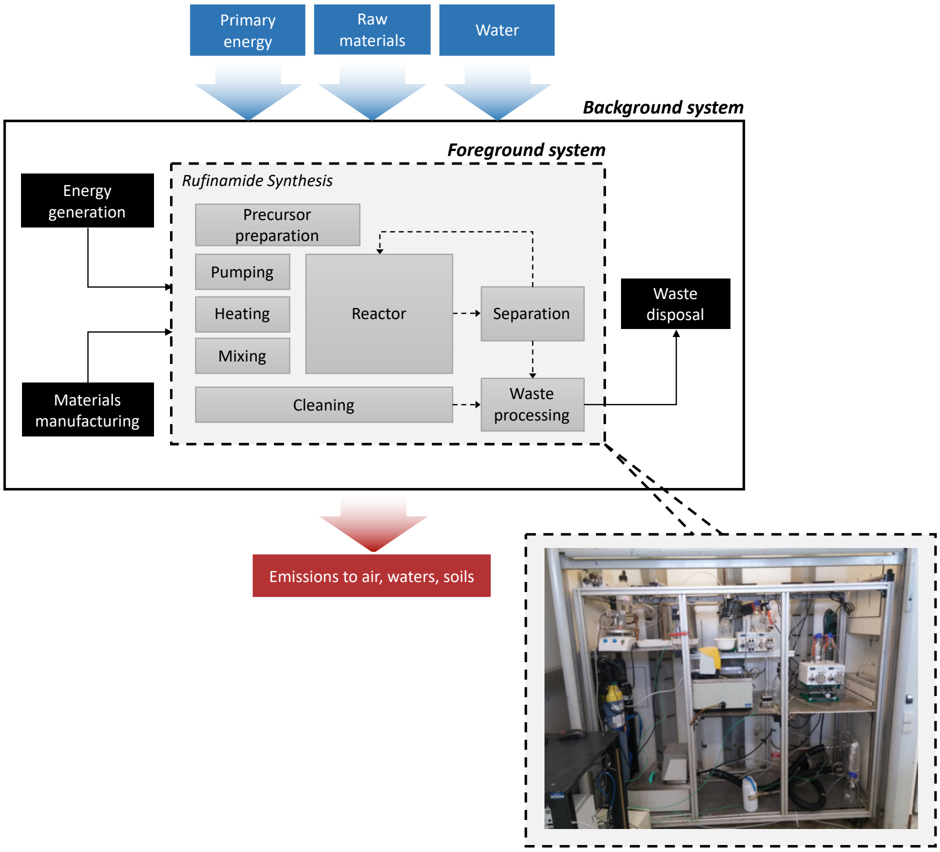


Figure 6.1 - System boundaries: foreground and background system. A picture of the mini-pilot plant is reported in the right-bottom corner.

These are subdivided into macro systems: foreground and background. The foreground system is composed by the array of operations occurring in the production phase, and by the production of chemicals. The background system is composed by the set of operations and services that revolve around the synthesis, namely, electricity production, raw materials extraction, and waste disposal. Each process is defined by compiling the material and energy balance occurring in them through the standardized approach indicated in the ISO 14040[190] and reported in Section 3.2.3.2.

- Environmental impact assessment

This phase translates the elementary flows described in the LCI (i.e. emissions or resource use) into an impact on the environment. LCIA results are expressed on the basis of the defined FU. LCI and LCIA were supported by the software tools GaBi ts 8.7 (SP36) professional + extensions (II, VI, IX, XVII) and Ecoinvent 3.6 (integrated SP36): the datasets are in compliance with the ISO 14044[71], ISO 14064[199] and ISO 14025[200] standards. In general, environmental impacts were estimated using a cradle-to-gate boundary for European production: in other words the activities that compose the life cycle (e.g electricity production) are region-specific and are modelled on the basis of European activities. LCIA was conducted applying the methodology "ReCiPe 2008" by Goedkoop[296] et al. in accordance with other studies[294] on Rufinamide production, in order to render coherent the benchmark with previous results. The results are expressed through the impact categories listed in Table 6.1.

Table 6.1 - List of impact categories used in the LCA with units and abbreviations.

Impact categories	**Units**	**Abbreviations**
Global warming potential	[kg CO_2-eq. per FU]	GWP
Fossil depletion potential	[kg oil-eq. per FU]	FDP
Freshwater eutrophication potential	[kg P-eq. per FU]	FEP
Human toxicity potential	[kg 1,4-DCB-eq. per FU]	HTP
Metal depletion potential	[kg Fe-eq. per FU]	MDP
Natural land transformation potential	[m^2 per FU]	NLTP
Ozone depletion potential	[kg CFC-11-eq. per FU]	ODP
Photochemical oxidant formation potential	[kg NMVOC per FU]	POFP
Terrestrial acidification potential	[kg SO2-eq. per FU]	TAP
Terrestrial ecotoxicity potential	[kg 1,4-DCB-eq. per FU]	TETP

LCIA methods essentially model the environmental mechanism that underlies each of the impact categories as a cause-effect chain starting from the environmental intervention (emission or physical interaction) all the way to its impact. To this end, the impact can be expressed through midpoint and endpoint methods, depending on type of output the analysis is meant to provide (i.e. increased chemical concentration in a lake vs extinction of species). As a general rule, the further the outcome of the assessment is expressed in the cause-effect chain, the more the results can be biased. In the present study, the chosen LCIA method imply a midpoint level assessment in order to minimize errors.

- Cost assessment

  The objective of performing a cost assessment is to provide enough information to make investment decisions. Besides selecting technologies with the biggest potential of economic return, early assessments can be used to assess risks, uncertainties or potential areas of improvement. In this work we considered two indicators in the cost evaluation of the continuous plant: the payback period (PBP) and the cumulative cash flow (CCF). In the assessment, several scenarios are investigated. These scenarios take into account the uncertainty of the cost of the raw materials, total investment costs and number of operators. Complementing the previous analysis[288], the impact of yield is evaluated under the same assumptions: straight line depreciation, useful life equal to 10, salvage cost of 0%, tax rate of 32%, interest rate of 0%. Furthermore, the same bulk prices are assumed.

At this stage, it is not possible to estimate additional costs such as regulatory and cleaning procedures. Consequently, it was assumed an additional 10% to the total costs (capital investment and raw material costs) to take into consideration these uncertainties, as reported by Escriba et. al[288].

With regard to calculations, the PBP is a methodology that estimates the amount of time to recover the investment, while the CCF estimates the sum of the cash flows in a determined period of time.

The PBP can be determined as follows[297].

$$PBP = \frac{C_{TC}}{A_{NCI}}$$

where A_{NCI} represents the annual cash income, C_{TC} the new investment. The A_{NCI} can be determined as follows[297].

$$A_{NCI} = A_{CS} - (A_{CS} - A_{BD})t$$

where A_{CS} represents the annual cost savings, A_{BD} the balance sheet depreciation and t the tax rate. The CCF can be determined by the sum of A_{NCI} in the period analyzed.

The evaluated scenarios use the following yields and reactant ratios (refer to Figure 6.2 for the synthesis steps):

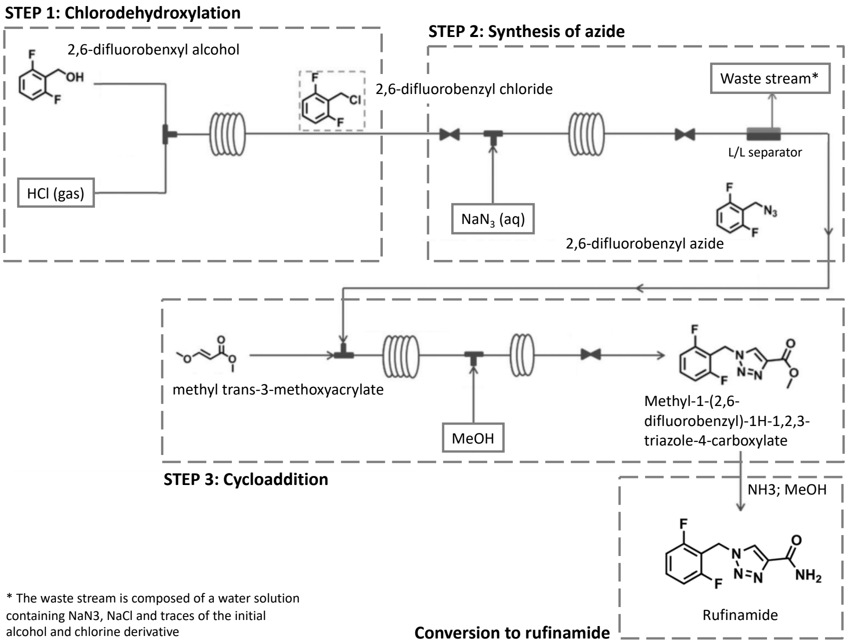
- Ideal plant, 100% yield and ratio of all reactants equal to 1.
- Lab plant, HCl:2,6-difluorobenzyl alcohol=1.2 and yield 99%; NaN_3:2,6-difluorobenzyl chloride=1.5 and yield 98%; methyl trans-3-methoxyacryate:2,6-difluorobenzyl azide=1.5 and yield 86%.
- Mini-pilot plant, HCl:2,6-difluorobenzyl alcohol=4 and yield 90%; NaN_3:2,6-difluorobenzyl chloride=1.6 and yield 99.4%; methyl trans-3-methoxyacryate:2,6-difluorobenzyl azide=1.5 and yield 93%.
- Worst case scenario, HCl:2,6-difluorobenzyl alcohol=2 and yield 90%; NaN_3:2,6-difluorobenzyl chloride=1.6 and yield 99.4%; methyl trans-3-methoxyacryate:2,6-difluorobenzyl azide=1.5 and yield 47%.

6.3.1.3 Comparative analysis

The environmental impacts and costs of the synthesis of Rufinamide are calculated for the lab and the mini-pilot scale. These are benchmarked against the environmental impact of the conventional batch synthesis. The results of the assessment of the CF system at mini-pilot scale are further analysed in a comparative analysis, showing the variations of the impacts depending on different overall yields and operative conditions. A hotspot analysis is also undertaken to identify the main causes of environmental impacts and costs. Scenario and uncertainty analysis are performed with the aim of identifying the variability of the system under variable inputs and operative conditions.

6.3.2 SYSTEM DEFINITION

Rufinamide is antiepileptic drug used to treat the Lennox–Gastaut syndrome and it was originally developed by Novartis Pharma. Several batch processes and synthetic routes have been described in patents[298–300]. However, these processes hinge on the use of expensive raw materials (i.e. dipolarophiles), are often characterized by high consumption of solvents and involve purification steps that have a large impact on the environment as they increase the generation of wastes[286]. In order to improve the environmental impact and the economics of the process, a solvent-free and continuous plant was developed[286–288,294]. A schematic representation of the CF synthesis of Rufinamide is reported in Figure 6.2.



* The waste stream is composed of a water solution containing NaN3, NaCl and traces of the initial alcohol and chlorine derivative

	Temperature		**Reactant ratio**		**Step yield**		
Synthesis step	*Lab*	*Mini-Pilot*	*Lab*	*Mini-Pilot*	*Lab*	*Mini-Pilot*	
STEP 1	110 °C	116 °C	HCl:2,6-difluorobenzyl alcohol=1.2:1	HCl:2,6-difluorobenzyl alcohol=4:1	99%	90%	
STEP 2	160 °C	200 °C	2,6-difluorobenzyl chloride:NaN_3=1:1.5	2,6-difluorobenzyl chloride:NaN_3=1:1.6	98%	>99%	
STEP 3	210 °C	175 °C	2,6-difluorobenzyl azide:methyl trans-3-methoxyacrylate=1:5	2,6-difluorobenzyl azide:methyl trans-3-methoxyacrylate=1:1.5	86%	52%-93%	
					~83%	~47%-83%	**Overall yield**

Figure 6.2 - Schematic representation of the CF setup and list of operative conditions and yields of the process for lab and mini-pilot scale.

The process consists of three continuous steps (continuous plant) plus an additional fourth step carried out in batch. Step 1 is the alcohol chlorination. This is performed in two phases (gas and liquid) and the end product obtained is 2,6-difluorobenzyl chloride. HCl (gas) is introduced into a heated CF reactor and it reacts with 2,6-difluorobenzyl alcohol (liquid). Step 2 is the azide substitution. In this step, 2,6-Difluorobenzyl chloride and sodium azide solution react to form 2,6-difluorobenzyl azide. Just as for the previous step, the reaction takes place in a two-phase system. The third step is the cycloaddition. In this step, 2,6-difluorobenzyl azide is mixed with methyl trans-3-methoxyacrylate and processed into the flow reactor. In order to carry out continuous synthesis and purification, a stream of methanol is introduced at the outlet of the reactor. Methyl-1-(2,6-difluorobenzyl)-1H-1,2,3-triazole-4-carboxylate is obtained. The last step is the conversion to Rufinamide. This last step is not part of the continuous plant. During the last step methyl-1-(2,6-difluorobenzyl)-1H-1,2,3-triazole-4-carboxylate is converted into 1-(2,6-Difluorobenzyl)-1H-1,2,3-triazole-4-carboxamide (Rufinamide) via reaction with ammonia, using methanol as solvent.

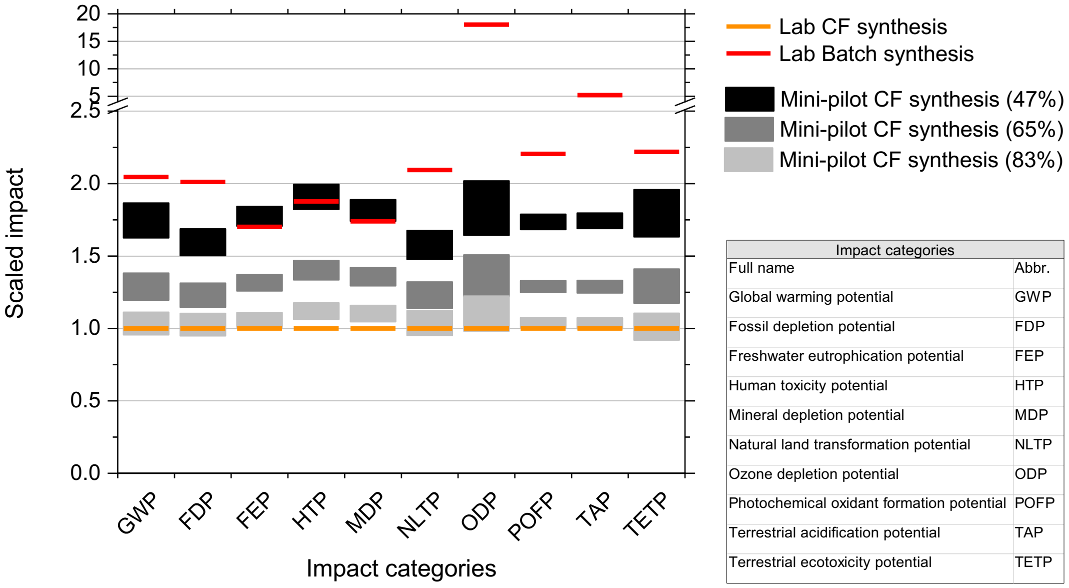
The CF process was originally developed at lab scale by Borukhova et al.[287] in the department of Chemical Engineering and Chemistry of the Technische Universiteit in Eindhoven, and it was later on scaled-up to a mini-pilot plant in collaboration with Microinnova GmbH (Austria). Figure 6.2 provides also a list of the different operative conditions followed in the lab and mini-pilot systems. The plant operates solvent-free with exception of Step 2, from the addition of NaN_3 to the L/L separator. As reported in previous publications[286,288], the scale-up process can lead to different mass and heat transfer coefficients which can have an impact on the yield. To this end, the proposed assessment investigates the effects that different operative conditions have on environmental impacts and costs. Furthermore, a scenario analysis is undertaken, considering as a variable the overall yield of the synthesis. Specifically, Step 3 of the synthesis process has shown in the trials a significant variation in the yield due to fouling of the reactor. This is likely to be overcome with further optimization of the reactor design. To this end, the chosen scenarios range from the lowest overall yield observed in the mini-pilot system (47%) to the best overall yield that was achieved in the lab scale (83%), as listed in Figure 6.2.

6.4 RESULTS AND DISCUSSION

6.4.1 ENVIRONMENTAL IMPACT ASSESSMENT

6.4.1.1 Technology comparison

The environmental impact of the CF synthesis of Rufinamide at lab scale and at mini-pilot scale are presented in Figure 6.3. These are normalized on the basis of the environmental impact of the CF synthesis at lab scale (baseline, in orange) and are expressed for each of the impact categories listed in the figure (in accordance with the work of Ott et al.[294]). Three scenarios are considered for the mini-pilot setup, referring to different process yields as a result of the uncertainties of the experimental results obtained in Step 3 (see 'System Definition, Figure 6.2'). These yields represent a pessimistic scenario (47%) in which the observed fouling issue cannot be mitigated, an optimistic scenario (83%) in which the overall yield of the mini-pilot system is equal to the overall yield observed in the lab system, and a mid-way scenario (65%).



Impact categories	
Full name	Abbr.
Global warming potential	GWP
Fossil depletion potential	FDP
Freshwater eutrophication potential	FEP
Human toxicity potential	HTP
Mineral depletion potential	MDP
Natural land transformation potential	NLTP
Ozone depletion potential	ODP
Photochemical oxidant formation potential	POFP
Terrestrial acidification potential	TAP
Terrestrial ecotoxicity potential	TETP

Figure 6.3 - Comparison of the environmental impact of the synthesis of Rufinamide. The results are reported for a conventional batch synthesis, and for the CF synthesis at a lab scale[294] and a mini-pilot scale. Three scenarios are given for the mini-pilot scale under different yields.

Furthermore, the proposed scenarios allow a potential deviation of 20% from the baseline (reported in Figure 6.2), for each one of the chemicals and operative conditions involved in the cycloaddition step, namely, methyl-trans-3-methylacrylate, methanol, NH_3, energy generation and waste management.

As shown in Figure 6.3, the environmental impact of the CF synthesis is significantly lower compared to the batch synthesis (red lines in the graph). With regard to the CF synthesis, the impacts associated to the mini-pilot system are generally higher compared to the lab system, in all the impact categories analyzed. To this end, low yields in Step 3 translates into higher environmental impacts. A detailed analysis on the primary causes of such increase is reported later in the hotspot analysis. It is worth noting that the optimistic scenario (83%) for the mini-pilot scale has still slightly higher (~6% on average) environmental impacts than lab CF system in all the impact categories. This additional impact can be looked at as the effect of the different operative conditions followed in the mini-pilot system, namely operative temperature and precursor ratios.

6.4.1.2 Hotspots analysis

A hotspot analysis of the environmental impact of the lab and mini-pilot CF system is reported in Figure 6.4. This looks at the contributions of the activities present in the life cycle of the synthesis of Rufinamide to the overall environmental impact. Following a similar approach as in Figure 6.3, the baseline is the environmental impact of the lab system[294] and the results of the LCA of the mini-pilot system are normalized accordingly.

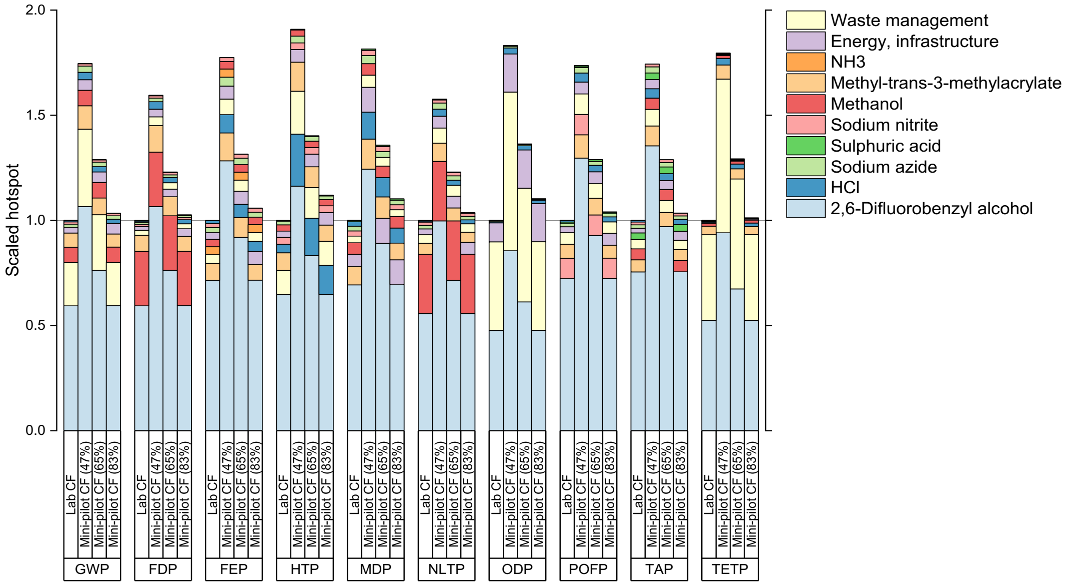


Figure 6.4 - Hotspot analysis of the environmental impact of the CF synthesis of Rufinamide. Three scenarios are reported for the mini-pilot scale (same as in Figure 6.3) under different yields.

The production of 2-6-diflorobenzyl alcohol takes on average more than 50% of the environmental impact of the CF synthesis of Rufinamide in all the impact categories. This compound is the main precursor and hence its impact is hardly mitigatable without changing the synthesis method or the way it is produced. Methanol and methyl trans-3-methoxyacrylate production, and energy generation take a significant share of the impact in Fossil Depletion Potential, Ozone Depletion Potential and Natural land transformation potential. Waste management is also a major contributor to the environmental impact of the systems. The waste generated is classified as hazardous waste and it is consequently disposed via incineration route that contributes to increase the impact especially in Global Warming Potential, Ozone Depletion Potential and Terrestrial Ecotoxicity Potential. To this end, the CF process requires lower volumes of solvents across the CF synthesis compared to conventional multi-step batch synthesis. The generation of waste is hence reduced, and this emerges clearly by looking at indicators such as E factor and solvent rate. These look respectively at the ratio of the total mass of waste to the mass of the isolated product, and the total mass of solvent to the mass of isolated product. In the CF process, both indicators are effectively reduced by a factor of 3.5 on average compared to the batch synthesis, with the final value being 17 ±2 and 19 ±3 respectively[294]. From a wider perspective, the E factor of the CF production of Rufinamide falls below the typical range of E factors of pharma products[290,292], attesting the reduction of the environmental footprint of the production process of Rufinamide when CF technology is used. Consequently, the CF synthesis emerges as a valid alternative to the batch synthesis of Rufinamide, and this should incentivize further efforts towards its deployment at commercial scale. Because of the potentialities shown in the efficient use of solvents and management of wastes, CF technologies could contribute, more in general, to reduce the environmental impact of other production processes in the pharma industry that still hinge on batch manufacturing. However, the results of this work cannot be generalized, and case-specific assessments are needed in order to evaluate the impact of CF technologies on other manufacturing processes.

It is worth noting that as the overall yield of the CF mini-pilot synthesis of Rufinamide decreases, the environmental impact arising from the production of chemicals and waste management drastically increases as a consequence of additional quantities of chemicals required and the higher volume of waste produced per kg of Rufinamide. When the effect of the synthesis yield is excluded, it is possible to capture further effects of the scale-up. This can be achieved by looking at the impact of the mini-pilot system (83%) and comparing it with the impact of the lab system in Figure 6.4. These two systems have the same overall yield but different operative conditions (see Figure 6.2 in 'System Definition'). On a closer look, the additional environmental impact of the mini-pilot system -less than 6% on average- results to be due to the production of HCl and energy generation. In other words, the main factors that contribute to the additional environmental impact of the mini-pilot plant are hence the higher ratio of HCl:2,6-difluorobenzyl alcohol in Step 1 of the synthesis, which is circa 3.3 times higher compared to the lab scale, and higher reaction temperatures. The excess of HCl also contributes to generate a higher volume of wastes. These drawbacks could be theoretically mitigated by implementing a recirculation system, and hence avoiding part of the impact arising from incineration activities. The feasibility of this option has not been proved yet. However, a successful implementation would reduce the environmental impact of the CF mini-pilot scale, hence potentially matching the environmental impact of the CF lab system. To this end, it is worth noting that the CF synthesis at mini-pilot scale showed on average a lower environmental impact than the batch synthesis (Figure 6.3) also in the worst-case scenario (47% yield). From the LCA perspective, the CF synthesis would enable savings of environmental impact in each of the impact categories of the analysis, and it is therefore advisable that this production technology is adopted.

Operative conditions, energy consumption, waste management and synthesis yield emerged as the most relevant aspects to factor into the assessment of the scale-up. To this end, the latter is well summarized in Figure 6.5 that reports the effect of these factors on Global Warming Potential and Human Toxicity Potential.

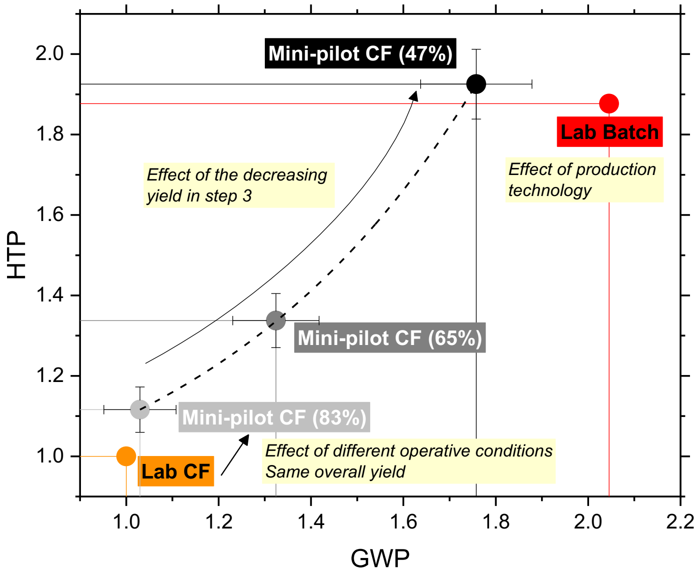


Figure 6.5 - Effects of production technologies, operative conditions and yields on GWP and HTP.

It is worth remembering that Step 3 is still to be optimized in the mini-pilot system and hence there is room for improvement. As reported in the section ‘System definition’, the main issue is the fouling of the reactor. This can be overcome through further optimization of the reactor’s design without impacting on the operative conditions of the system. By looking at Figure 6.5, it is clear that low yields in Step 3 of the synthesis highly affect the environmental impact of the system in the selected impact categories. In the light of this, the optimization of this step should be prioritized for the development of a low impacting production system in the next phases of the scale-up.

6.4.2 COST ASSESSMENT

The reduction of the cost of the raw materials is the main business driver for the CF synthesis of Rufinamide. The analysis considered two plants (batch and CF) with an equal capacity of 10 ton/y. The yearly costs of the raw materials had been estimated to be $924k and $1432k for the continuous flow and batch plants respectively[288]. The bulk price of the raw materials was estimated using the correlation proposed by Hart et. al as seen in Eq. 3[301]. This equation estimates the bulk price of the products based on the price at lab scale, where the index B represents the commercial scale and l lab scale, P represents the price, and Q_l is the amount of grams at lab scale and Q_B is a constant equal to 60 lb.

$$P_B = P_l \left(\frac{Q_B}{Q_l}\right)^{-0.75}$$

The previous cost estimations considered a fixed overall yield of 80% for the continuous plant. To this end, Figure 6.6 reports the annual expenditure on raw materials considering the potential variation in yields.

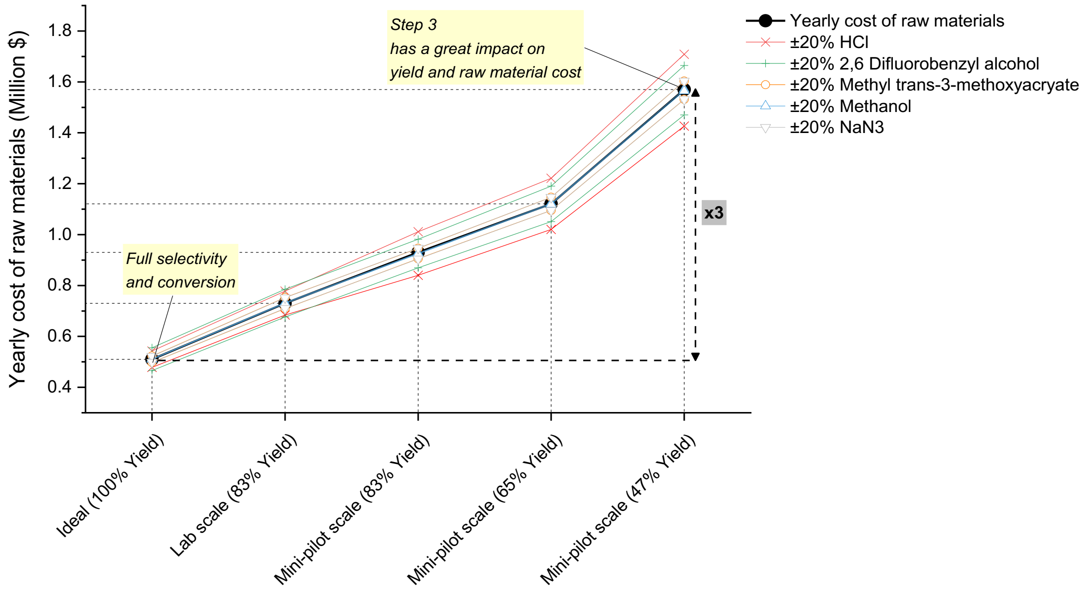


Figure 6.6 - Yearly cost of raw materials under different scenarios in the CF process.

The scenario referring to pilot scale with 47% yield has the highest raw materials costs as it would be expected (lowest yield, worst case scenario). In this scenario, the annual expenses are in fact even higher than the annual expenses estimated for the batch process without considering recirculation of the reagents[288]. However, the estimation of the batch process is based on results at lab scale and no information was found at larger scales[300].

Figure 6.6 also highlights the importance of having an optimized yield in Step 3 of the synthesis. These results have a great impact on the use of raw materials, which take the highest share of the total costs. Additionally, Figure 6.6 shows the impact of the uncertainty on the cost estimation for each single raw material. It is observed that HCl(gas) has the highest impact and potential savings. This result requires as a next step to determine the commercial price of this specific raw material. In case the actual prices do not deviate greatly from the estimated ones, it could be helpful to take a step back and rethink if HCl (aq.) could be used instead as a mean to reduce costs even further, which has already been proven to be feasible before[15]. This approach would make a compromise between profitability and sustainability of the process (HCl in liquid phase produces water as waste).

Figure 6.7 shows the CCF under different case scenarios.

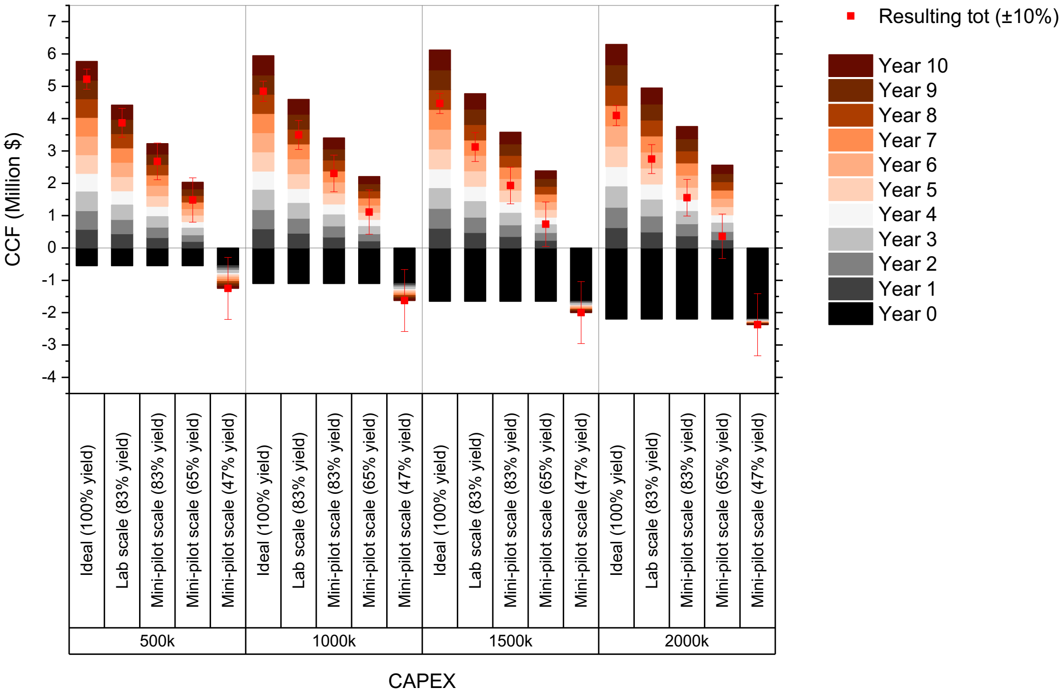


Figure 6.7 - Cumulative cash flow for different yields in the CF process, and different CAPEX investments.

Figure 6.7 also shows the impact on uncertainty of the raw materials costs (±10%) of the CF plant. The worst-case scenario (yield 47%) does not provide a positive CCF under the assumptions analyzed in most of the scenarios evaluated. Additionally, without considering the worst-case scenario, the PBP was below 4-5 years in most of the cases. The cost of the raw materials is expected to have the biggest impact on the plant as reported by Escriba et al.[288] and small variations on the estimations can have a major impact on the profitability of the project and it highlights the need to improve the yield of the third reaction step and to estimate as accurate as possible the cost of the raw materials.

6.5 CONCLUSIONS

The findings of this study emphasize the usefulness of assessing emerging technologies early in the technology development: the assessment has shown that the outcome (environmental performances and costs) can be effectively used as direct input to the process development and guide it towards the optimization of the system. As anticipated in Chapter 3, this is one of the main expected outcomes of this type of assessment: integrating the technology development with environmental and economic inputs, in order to maximise the sustainability of the emerging technology under analysis.

The results put also in evidence the effect of the scale on environmental impacts and costs of a production system during the technology development. The chapter reported in fact a life cycle assessment and cost evaluation of the continuous flow synthesis of Rufinamide at two different scales: a lab scale and a mini-pilot scale. It is the first time that this synthesis is evaluated at pilot-scale. To this end, a scenario analysis and a hotspot analysis were undertaken to investigate the variation of the results and to identify the key parameters of the synthesis.

The assessment shows that, under the same overall yield, the CF mini-pilot plant has marginally higher environmental impacts and costs per kg of Rufinamide produced compared to the CF lab system. The mini-pilot plant adopts higher operative temperatures and ratio of reactant-to-precursor that translate into larger quantities of chemicals processed, additional energy consumption, and hence increased costs and effect on the environment. The increase though is marginal and the environmental impact and costs of the CF synthesis of Rufinamide at pilot scale remain significantly lower compared to a conventional batch synthesis. The lower impact stems in large part from the generation of waste, which is effectively mitigated in the CF system. In the latter the E factor is significantly lower than a conventional batch synthesis, and more generally falls below the typical range of E factors of pharma products. In light of this, it is hence advisable that the CF production technology is adopted in place of the conventional batch synthesis of Rufinamide. However, the last step of the CF synthesis– the cycloaddition – has a strong effect on the performances of the mini-pilot plant and hence emerges from the assessment as the key factor for achieving low environmental impacts and generating good return on investment. Therefore, the next phase of the process development should prioritize the optimization of the cycloaddition step.

The next chapter will introduce another example of process intensification, investigating further on the transition from batch to intensified continuous flow processing. As outlined in the introduction of the Thesis, this transition is currently being looked at in great detail by many academics and in the industrial sectors, as in the case of the recent EU project COSMIC that brought together the joint effort of a number of European companies and universities under a consortium with focus on intensified continuous flow processing. To this end, the next case study results from a collaborative partnership with Arkema - a company with specialty in chemicals and advanced materials - as part of the latter consortium, that opened at the possibility to perform the assessment proposed in Chapter 3 to a full pilot plant developed in their research facilities.

7 CASE IV - INTENSIFIED PRODUCTION OF ZEOLITE A

The content of this Chapter is currently under revision in the Journal of Industrial Ecology, including a supporting information document containing the inventory data of the work: *Grimaldi, F. Ramirez, H., Lutz, C., Lettieri, P., 2020. Intensified Production of Zeolite A: Prospective Life Cycle Assessment of a Continuous Flow Pilot Plant and Comparison with a Conventional Batch Plant.*

7.1 CHAPTER SUMMARY

Following up on the previous case studies, Chapter 7 brings on the discussion on the transition from batch to continuous flow processing started in Chapter 5 (batch vs CF processing at lab scale for the production of gold nanoparticles), carried on in Chapter 6 (batch vs CF processing at mini-pilot scale for the production of Rufinamide), and moves the discussion on a full pilot scale. The system under analysis originates from the research facilities of Arkema (GRL in Lacq, France) where a CF production system for the production of zeolite A is being developed. The case study is the results of a secondment at the mentioned facilities during which full access to the pilot plant was granted. Furthermore, during the secondment, it was possible to compile a complete LCI on Arkema's current commercial plant based on batch production. The objective, in this case, was to compare the performances of the two systems and hence understand the possible consequences of adopting the CF system as integration or in substitution of the batch system at commercial scale.

On the whole, this case study interlaces two different macro topics: the transition from batch to continuous flow processing and the application of the assessment of emerging technology at full pilot scale (TRL 5). Specifically, the technology under consideration is an oscillatory continuous-flow synthesis for the production of zeolite A, one of the largest zeolites employed worldwide by volume and value.

As established in the previous chapters, the LCA is used to measure the environmental impact of this emerging technology in an anticipatory fashion, before its fully deployment. The assessment explores the whole life cycle of the production system and comprises a normalisation analysis, which frames the environmental impacts of the production system in the European context, a scenario analysis, and a hotspot analysis. Finally, the continuous-flow technology is benchmarked against the environmental impact of a conventional batch production of zeolite A, based on a full-scale commercial plant.

The results show that significant advantages would stem from shifting from batch to continuous-flow production. In the latter, the environmental impact is reduced in the impact categories that carry most of the impact of the life cycle of Zeolite A, namely human toxicity and ecotoxicity of freshwater. However, a large share of the total environmental impact hinges on the production of NaOH, a building block of the synthesis, and hence is hardly mitigatable. On the whole, the findings of this work emphasize the need of integrating LCA during the development phase of emerging technologies in industrial R&D with the aim of optimizing the environmental performances of these systems and therefore increase their attractiveness for deployment and introduction in the market.

7.2 INTRODUCTION

Process Intensification (PI) has experienced a ceaseless growth over the last two decades. PI is considered to be one of the most promising routes for the development of sustainable chemical processes[22]. There are several definitions of process intensification in the literature, each one capturing a different aspect of its application. Among these, however, practice and applications have, over time, helped forging a broader definition of PI as: "Any chemical engineering development that leads to substantially smaller, cleaner, safer and more energy efficient technology"[20,23]. It is therefore expected that intensified processes have reduced CAPEX and smaller environmental footprint than their conventional counterparts. In such intensified systems, reduced physical dimensions ensure that transport limitations are minimized and processes are governed by their intrinsic rates, and all molecules experience the same processing conditions[22,302].

To this end, advanced continuous-flow (CF) technologies, both at micro/milli-scale[25–27] and larger scale[28,29,303], are considered examples of process intensification, and are often developed as alternatives to conventional batch technologies. A number of advanced CF technologies have been proposed over the past recent years as alternative, intensified solutions to the manufacturing of products in various industrial areas. The targeted systems are often those batch-type technologies that have been the conventional way of production for many years and hence are often not prone to changes. The transition to continuous processing promises improvements over the century-old batch processing technology with lower energy consumption, reduced waste generation and exposure hazards, smaller environmental footprint, lower investments and more controllable product quality. This transition from batch to CF production is a process intensification step that is currently being looked at in great detail by many academics and in the industrial sectors (e.g. 'COSMIC' project as part of the Horizon 2020 program[24]).

In this study, we focus on the manufacturing of zeolite Linde Type A (Zeolite LTA or Zeolite A), one of the largest zeolites employed by volume and value[304]. The most common form of zeolite LTA has a Si/Al ratio of 1, which means a potential high cation exchange capacity[305]. Other characteristics include thermal stability, high selectivity, non-toxicity, and good mechanical strength[306]. This product is widely used in detergent industry for water softening[307], as well as to remove calcium and magnesium from hard water to prevent precipitation of insoluble salts on piping and equipment[308]. It is also used in industry for the dehydration of ethanol/water mixtures near the azeotropic composition[309], which constitutes one of the most expensive steps in biofuel production[310]. Moreover, zeolite LTA is widely used for dehydration of natural gas and sweetening[311].

The conventional production method is batch-type where alkaline solutions of sodium silicate and sodium aluminate are mixed together and then hydrothermally treated at around 100°C[312]. Increasing attention is being paid to the intensification of this process, focusing on the transition to a continuous process that allows controlling the mean size and particle size distribution of crystals. Besides, a continuous installation will be more compact and more flexible, offering the possibility to increase the production capacity by duplicating the operation unit. To this end, Arkema is developing a CF installation able to match and enhance the current zeolite LTA production system. The continuous installation is characterized by the in-line mixing of the reactant and the in-line seeding of the synthesis gel solution. Moreover, a continuous oscillatory baffled reactor is integrated to carry out the hydrothermal treatment at high temperature.

The application of CF technology to the synthesis of zeolite A is an example of PI and is being investigated with increasing attention because of its interesting features such as high controllability of the product quality, ease of operation and efficiency in the recovery of energy and valuable material streams[313]. However, an intensified process is not automatically synonym of lower environmental footprint. Not all processes reach in fact commercial scale, and this translates into loss of human and capital resources. Furthermore, their development can be costly, time consuming and involve long procedures for their implementation[35].

In light of this, emerging technologies need to be filtered since the first stages of their development in order to avoid waste of resources that translates into poor environmental performances, increased operational costs and reduce competitiveness. To this end, an efficient screening and selection of emerging technologies at early stages requires a high level of process knowledge, and this poses several challenges regarding the availability of data and the inherent uncertainties caused by process designs yet to be completed[314,315]. Such knowledge and data, in fact, are usually only available at later stages of their development[268].

This calls for the need of "prospective" assessments that quantifies the environmental impacts of a system since early stages of the process development, i.e. on the lower end of the Technology Readiness Level (TRL). Through this approach, the performances of the system under analysis can be benchmarked against the standard industrial practice, thus quantifying the benefits stemming from the adoption of such innovative production technologies in place of conventional ones.

To this end, the field of process intensification offers a great number of promising technologies that call for all-round assessments able to determine in an anticipatory fashion their future environmental and economic performance. As pointed out before, the environmental impacts of these novel technologies need to be benchmarked with the state-of-the-art technologies; as in the case of identifying the possible associated benefits of intensified continuous flow technologies over batch systems. In response to this, a series of papers has been published on the assessment of novel production systems originating from both academic [316] and industrial R&D [268] at TRLs 3-4 (bench-scale and mini-pilot scale).

Following up on the application of LCA of emerging technologies, in this case study, the LCA methodology is applied to the intensified continuous flow production of zeolite A at full industrial pilot scale (TRL 5). The aim is to provide a projection of the environmental performances of this novel production technology, benchmark it against the standard production system conventionally adopted in industrial production, and hence provide an understanding of the consequences of its full exploitation at large scale.

To the best of the authors' knowledge, no LCA on the CF production of zeolite A at large scale have been published yet. In this work, the synthesis of zeolite A is investigated by taking into consideration two production systems, the conventional batch synthesis and an innovative CF synthesis. The batch system is sized on an existing commercial plant and it is taken as the reference case, while the CF system refers to a pilot plant that is being developed by Arkema, at GRL facilities in Lacq. Both systems are subjected to LCA and are compared. The whole set of operations typically involved in an industrial plant are considered: cleaning, separation, energy and material recovery. In addition, the modelling of the life cycle of the production systems comprises all the peripheral activities at support to the synthesis of zeolite A, such as the production of chemicals, energy generation, raw material extraction, transport and waste treatment.

The work is structured as follow:

- Material and methods

  In this section the concept of the work is presented, and the methodology of assessment is explained in detail. The batch and CF production systems are described; the inventorial information is derived and used for the calculation of environmental impacts. This section provides the procedure followed and the assumption made for the calculation of the environmental impacts and uncertainties, and also reports the information about the construction of the LCA model.

- Results and discussion

  The results of the LCA are presented and discussed. The environmental impacts are reported by means of a scenario analysis, normalisation, hotspot analysis and comparative analysis.
- Conclusions

7.3 MATERIAL AND METHODS

7.3.1 FRAMEWORK

The structure of the present work is represented in Figure 7.1. It consists of three main phases, namely, system definition, assessment, and comparative analysis, on the basis of the framework presented in Section 3.2.

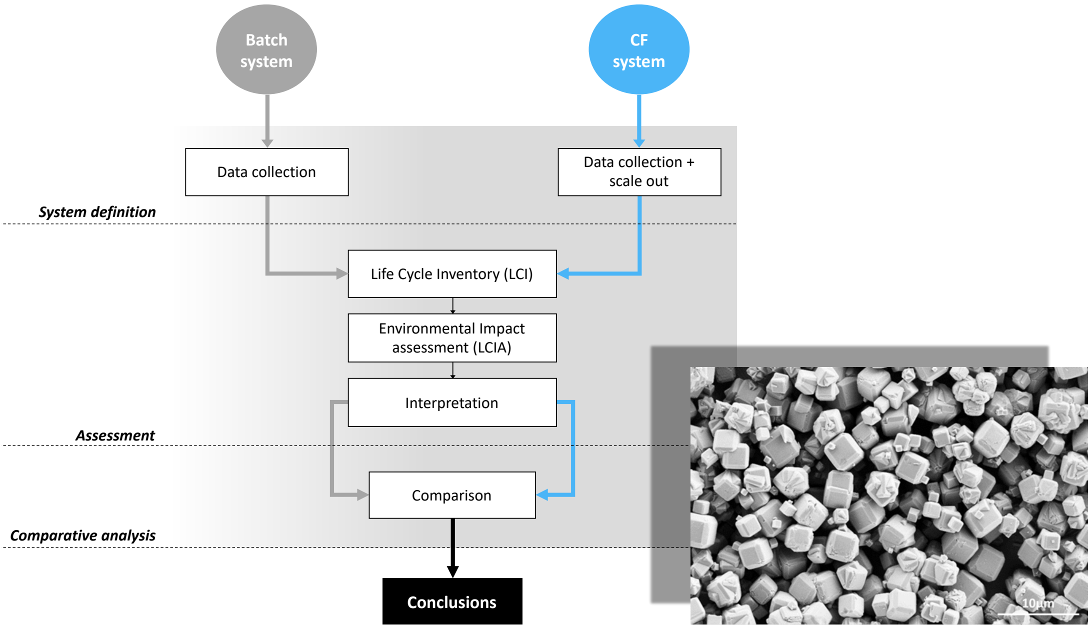


Figure 7.1 - Framework: system definition, assessment and comparative analysis. In the bottom-right corner, Zeolite LTA crystals: scanning electron microscopy image of a sample prepared at GRL facilities, ARKEMA.

In the next sections these phases will be analysed in detail, touching on the methodological recommendations as well as on the procedures followed for the calculation of quantitative data.

7.3.1.1 System definition

In this step the process flow diagrams (PFD) are defined and described in detail for both the emerging and conventional technologies. Specifically, the batch system is sized on a commercial plant with a reference production of 1 kton of zeolite A per year and its scale is used as the reference for the CF system. In the case of the CF system, the construction of the PFD is originated from a full pilot plant and scaled out to the reference productivity of the batch system (1 kton of zeolite A per year). For both systems, the data necessary to compile the LCI was collected in the Arkema facilities of GRL in Lacq, France. A high level of detail is provided in this phase with regard to the emerging technology; as remarked in the previous section, the robustness of the data inventory is crucial for enabling a coherent assessment. To this end, the collection of data was undertaken directly on-site by means of a secondment period in order to grant reliable data, quantify the uncertainties and gain general knowledge on the process, necessary for the compilation of the inventorial information. The full set of operations involved in a full-scale PFD is taken into account, namely, the precursors' preparation, pumping, synthesis, heating and mixing, cleaning, separation, recycling, transport, waste disposal and packaging.

The resulting information is organised in the Life Cycle Inventory (LCI).

7.3.1.2 Assessment phase

- Life Cycle Inventory

  The chosen FU for this study is 1 kton of zeolite A. This FU is used for the batch and CF production systems as they have the same productivity. The data for the LCI is collected or calculated for each unit process included into the defined system boundaries (Figure 7.2). These consist of two sub-systems: foreground and background systems. The foreground system includes the set of activities that take part directly to the production: precursor preparation, pumping, heating, mixing, separation, cleaning, packaging, transport and waste processing. The background system comprises the activities that support indirectly the synthesis such as raw materials extraction, chemical production, electricity production, and waste disposal.

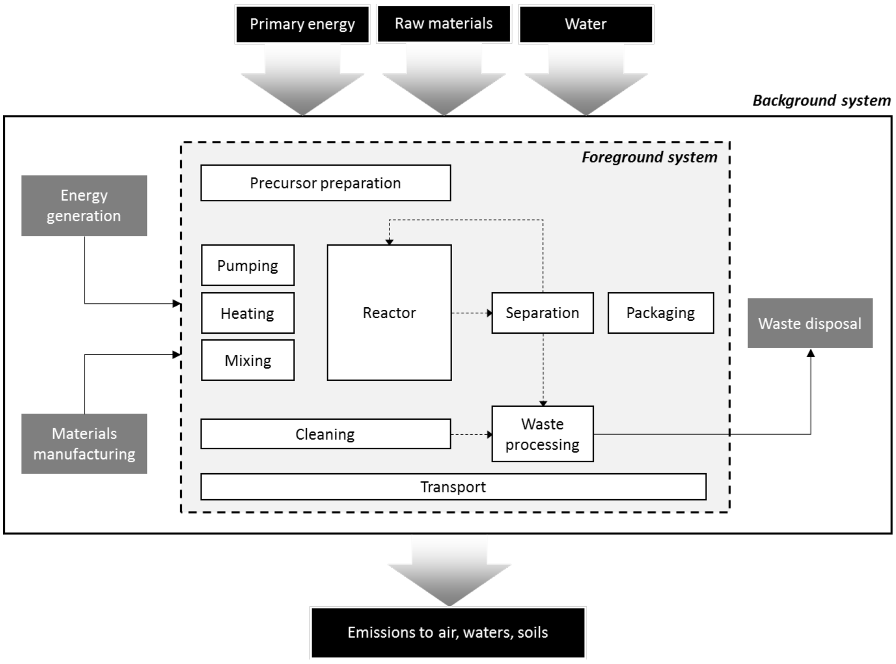


Figure 7.2 - System boundaries: foreground and background systems.

The functional unit and the system boundaries defined are the same for both continuous flow and batch systems, that is a requirement for achieving a coherent comparison.

- Environmental impact assessment

  The environmental impacts are calculated through the LCIA method 'ILCD/PEF recommendation 1.09'[72]. This method has been proven to be reliable, is recent and has received large consensus in the last few years. It uses midpoint indicators: in other words, the quantitative modelling of the environmental consequences of an emission stops at a mid-point in the cause-effect chain. This limit the uncertainties in the calculation of the environmental impacts as less assumption are made on the effects on the environment.

  The LCIA associates an impact on the environment to each one of the flows that have been identified and described in the life cycle inventory. The environmental impact is expressed for different impact categories reported in Table 7.1.

Table 7.1 - Impact categories used for the LCIA and description: the impact categories are selected from the LCIA method 'ILCD/PEF recommendation 1.09'.

Impact category	Description	Unit	Abbr.
Acidification	It is mainly caused by air emissions of NH3, NO2 and SOx.	[mole H^+ eq.]	A
Climate change, excluding biogenic carbon	Contributions of the greenhouse gases to the global warming and climate change	[kg CO_2 eq.]	CC
Ecotoxicity freshwater midpoint	Toxic effect on aquatic freshwater species in the water ecosystems.	[CTUe]	EcoTOX
Eutrophication freshwater midpoint	Eutrophication effects in the freshwater compartment.	[kg P eq.]	E fw
Eutrophication marine midpoint	Eutrophication effects in the marine compartment.	[kg N eq.]	E mw
Eutrophication terrestrial midpoint	Eutrophication effects in the terrestrial compartment.	[mole N eq.]	E t
Human toxicity midpoint, cancer effects	Toxic effect on humans referring to potential cancer effects.	[CTUh]	HT c
Human toxicity midpoint, non-cancer effects	Toxic effect on humans referring to potential non-cancer effects.	[CTUh]	HT non-c
Ozone depletion	Depletion of the ozone layer at the stratosphere level.	[kg CFC-11 eq.]	OD
Particulate matter	Direct and indirect contribution to particulate matter formation	[kg PM2.5 eq.]	PM
Photochemical ozone formation midpoint	Contributions of VOC (volatile organic compounds) and non-VOC to the formation of ozone at troposphere level.	[kg NMVOC eq.]	POF
Resource depletion, water	Water resource depletion.	[m^3]	RD water
Resource depletion, minerals, fossils and renewables	Depletion of mineral and fossil resources.	[kg Sb eq.]	RD m, f, ren

Finally, the software adopted for the built of the LCA model is GaBi ts 8.7 (SP36). Processes and materials used in the model comes from the databases professional + extensions (II, VI, IX, XVII) and Ecoinvent 3.6 (integrated SP36): the dataset are in compliance with the ISO 14044[71], ISO 14064[199] and ISO 14025[200] standards and up to date. All the results reported in this work refer to 1 kton of zeolite A product, which is the chosen Functional Unit. This contextualises the environmental impacts of the production of zeolite A in the broader context of European emissions.

7.3.1.3 Comparative analysis

In this phase the results of the assessment of the batch and CF systems are further analysed and then compared. Normalisation and uncertainty analyses are undertaken. The normalisation analysis is performed on the basis of the calculation showed previously in the general framework in Section 3.2.3.2. This analysis serves the purpose of (1) comparing the environmental impact of the system under analysis to the impact resulting from the activities in a defined region (in this case Europe); (2) enabling a comparison of the impact across different impact categories. The normalisation analysis is integrated with a scenario analysis that investigates on the environmental performances of the batch and CF systems under different efficiencies of the recirculation system in order to test the sensitivity of the system, understand under which condition the CF system would bring advantages over conventional systems and hence be deployed.

In this phase an uncertainty analysis quantifies the uncertainties that affect the system under consideration; these are mainly attributable to the variability of the data collected and to the assumption made for the calculation of the data not directly available for the inventory. The results of the analysis are embedded in the charts reported in the 'Results and discussion' section (7.4).

Furthermore, a hotspot analysis is performed to generate the highest level of detail. This investigates the main activities responsible for the environmental impacts in the life cycle of the two systems. The hotspots analysis provides information on the possible intervention points in the technology development, both in terms of life-cycle phases (e.g. transport, production phase, waste treatment) and in terms of specific activities taking part to the life cycle of the production system (e.g. preparation of precursor, pumping, hazardous waste incineration, etc.). The underlying concept is to enable an "optimisation loop" (as showed in Figure 3.2) with process information and projected environmental impacts travelling back and forth between process development and assessment phase, thus contributing to maximising the environmental performances of the emerging technology before the latter enters the market.

The outputs of these analyses are compared and discussed for both systems under analysis.

7.3.2 SYSTEM DEFINITION

The productive system taken as reference for this study is a batch commercial plant capable of producing around 1 kton of Zeolite LTA (dry weight) per year. The synthesis of zeolite LTA involves the hydrothermal crystallization of aluminosilicate gels (formed upon mixing between alkaline aluminate and silicate solutions). The precursors, sodium aluminate and sodium silicate, are mixed in a batch reactor at around 35°C to form the synthesis gel which is then heated to be crystallized at 100°C and a zeolite slurry is formed. A buffer tank regulates the flow of the zeolite slurry downstream of the reaction step.

Subsequently, the resulting flow is processed into the separation step that is composed by a set of operative units treating the slurry and refining it to obtain the final product. Specifically, the slurry is firstly adjusted in terms of water content by means of filtration where a zeolite cake is obtained. The cake is then dried obtaining zeolite powder. Afterwards, the resulting powder is treated via grinding and the final product is collected. A simplified representation of the PFD is reported in Figure 7.3, which shows the process configuration adopted in the batch system as well as in the continuous flow synthesis.

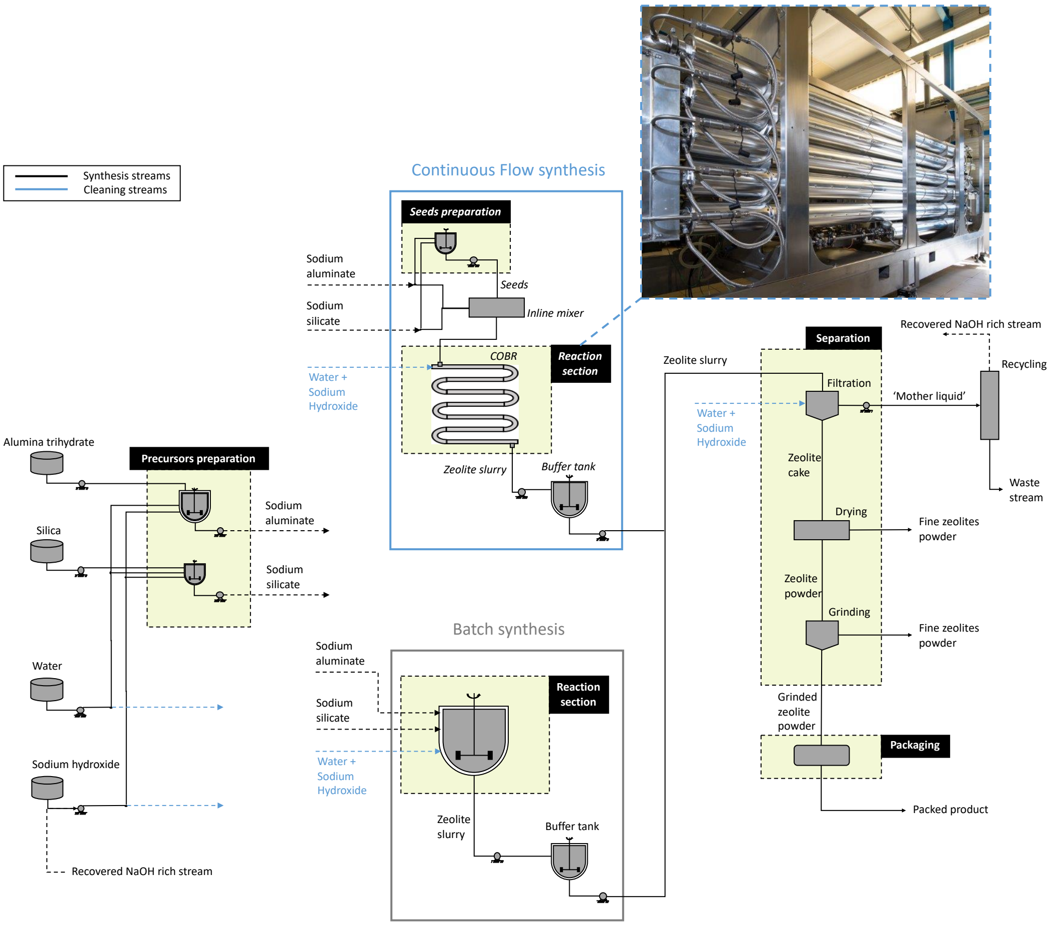


Figure 7.3 - Simplified PFD, batch and continuous flow production. The continuous oscillatory baffled reactor (COBR) used at GRL facilities in Lacq is shown in the top-right corner.

In the flow setup (top section of Figure 7.3), a set of parallel continuous oscillatory baffled reactors (COBRs) replaces the vessel that served the purpose of the synthesis gel preparation and crystallization in the batch system. These operations occur in one step in the CF reactor. The latter differs also from the batch reactor for the in-line mixing of the reagents and the in-line seeding of the synthesis gel. The concentration of both sodium aluminate and sodium silicate is also lowered in order to grant the right viscosity of the mixture entering the reaction phase. The content of sodium hydroxide is increased accordingly to keep unvaried the alkalinity. The resulting stream is then sent to the COBRs where the growth of crystals is achieved. Precursor preparation and separation phases remain unaltered as the CF system is meant to be integrated into the existing commercial plant.

A recirculation system is currently being tested for both systems, and aims at recovering part of the sodium hydroxide from the effluent after the filtration step of the separation ('Mother liquid'). This, in fact, is rich in sodium hydroxide that is required in large volumes during the synthesis. Despite not being fully assessed yet, the recirculation system is considered part of both systems in this study. The resulting variability that such addition brings to the LCI is taken into account by means of a scenario analysis, presented in the next sections, considering different recirculation efficiencies. Specifically, the selected recycling efficiencies are 0% and 30% for the batch system, and 80% and 95% for the CF system; these efficiencies reflect the different technical feasibility of adopting a recycling system in the two systems, and represent the most likely scenarios.

A breakdown of the material and energy requirements related to the two systems described above is reported in Table 7.2 and Table 7.3.

Table 7.2 - Inventory, batch system (30% recycling).

Group	Item	Stage	Quantities per kton of zeolite A (dry weight)	
Chemicals	Alumina trihydrated	Precursor Prep.	526	*t*
	Sodium silicate	Precursor Prep.	1501	
	NaOH solution 50 wt%	Precursor Prep.	278	
	Water use	Precursor Prep + Reaction section	2960	
Cleaning	Water use	Vessels + separation	30171	*t*
	Soda 100%		280	
Energy consumption	Natural Gas (Heating)	Precursor Prep + Reaction section	331	*MWh*
		Separation	41	
	Electricity (Mixing)	Precursor Prep + Reaction section	24	
		Separation	69	
	Electricity (Pumping)	Precursor Prep + Reaction section	31	*MWh*
		Cleaning	8	
		Separation	13	
		Mother liquid recycling	3	
Disposal	Mother liquid		21793	m^3

Table 7.3 - Inventory, continuous flow system (95% recycling).

Group	Item	Stage	Quantities per kton of zeolite A (dry weight)	
Chemicals	Alumina trihydrated	Precursor Prep.	526	*t*
	Sodium silicate	Precursor Prep.	1606	
	NaOH solution 50 wt%	Precursor Prep.+ Seeds Prep.	80	
	Water use	Precursor Prep.+ Seeds Prep.	9143	
Cleaning	Water use	Vessels, COBR + separation	27756	*t*
	Soda 100%		83	
Energy consumption	Natural Gas (Heating)	Precursor Prep + Reaction section	27	*MWh*
		Separation	41	
	Electricity (Mixing)	Precursor Prep + Reaction section	28	
		Separation	69	
	Electricity (Pumping)	Precursor Prep + Reaction section	26	*MWh*
		Cleaning	8	
		Separation	13	
		Mother liquid recycling	3	
Disposal	Mother liquid		4670	m^3

7.4 RESULTS AND DISCUSSION

The results of the LCA are divided into three sub-sections, each one offering a different perspective on the environmental impact of zeolite A production:

- Normalisation

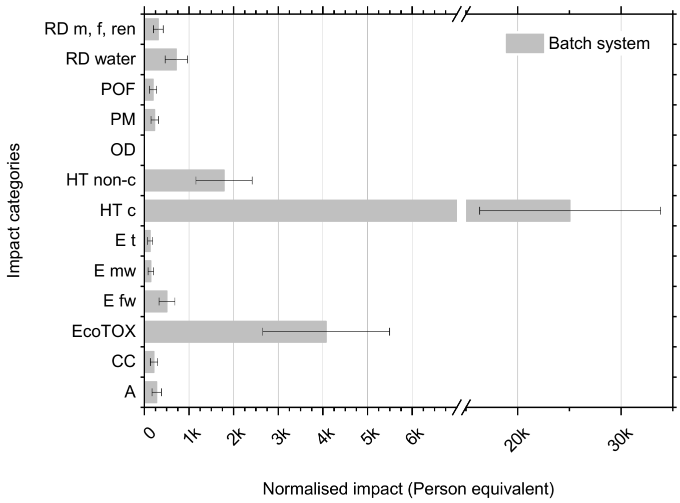
  This section contextualises the environmental impacts of the production of zeolite A in the broader context of European emissions.
- Technology comparison and scenario analysis

  The absolute environmental impacts of the batch and continuous flow production technologies are compared and discussed.
- Hotspot analysis

  A hotspot analysis is undertaken. The goal of this section is identifying the causes of the environmental impacts of the production systems.

7.4.1 NORMALISATION

The results of the normalisation weigh the environmental impact of the system under analysis on the overall environmental impact arising from the activities of a region – in this case Europe. Through the normalisation, environmental impacts are expressed in person equivalent. The results of the normalisation are showed in Figure 7.4 for the batch production system.



Abbr.	Impact categories	Share of the total impact	Relevance
HT c	Human toxicity, cancer effects	73.0%	HIGH
EcoTOX	Ecotoxicity freshwater	11.9%	
HT non-c	Human toxicity, non-cancer effects	5.3%	MODERATE
RD w	Resource depletion water	2.1%	
E fw	Eutrophication freshwater	1.5%	
RD m, f, ren	Resource depletion, mineral, fossils and renewables	0.9%	LOW
A	Acidification	0.9%	
PM	Particulate matter	0.7%	
CC	Climate change	0.7%	
POF	Photochemical ozone formation, human health	0.7%	
E mw	Eutrophication marine	0.5%	
E t	Eutrophication terrestrial	0.5%	
OD	Ozone depletion	0.0%	

Figure 7.4 - Normalised environmental impacts of the batch production system and share of the total impact for each impact category.

As reported in 5.4.1.1, the bars in the graph represent the normalised environmental impact of the production of 1 kton of zeolite. Each bar of the graph in Figure 7.4 is obtained by diving the environmental impact of the production system in a specific impact category by the environmental impact of all European activities; the number obtained –that is the share of the total environmental impact arising from Europe – is then multiplied by the European population. Therefore, a major output of the normalisation is that it enables a comparison of the environmental impacts across different impact categories and hence it is possible to have a criterion of selection of the impact categories of major relevance.

In order to enable such selection, it is necessary to look at the shares of the total impact of the batch production for each impact category considered in the analysis. The total impact of a production system is the sum of the normalised impacts of all the impact categories. The total impacts of the batch production is 33.7k person equivalent. Consequently, the share of the total impact for each impact categories is obtained by dividing the normalised impact of a given impact category by the total impact of the production system. For example, the normalised impact for Human Toxicity (cancer effects) in the batch system is 25k person equivalent and hence the share of the total impact is 73%. The same procedure is followed for the rest of the impact categories and the results are reported in Figure 7.4 (right side). The highest shares of the impact are taken by Human Toxicity (cancer effects) and Ecotoxicity of freshwater. Human toxicity (non-cancer effects), Resource Depletion (water) and Eutrophication of freshwater take a moderate portion of the total impact while the rest of the impact categories have negligible effects on the total impact.

7.4.2 TECHNOLOGY COMPARISON

Following up on the results of the normalisation analysis, Figure 7.5 shows a comparative analysis of the environmental impacts of batch and CF production (referred to the chosen FU of 1 kton of zeolite A). Conversely, to the normalisation analysis, this comparative analysis reports the environmental impacts with the units typical of each impact category. Hence, the comparison across impact categories is not allowed in this case; the columns in Figure 7.5 can be only compared within the same impact category.

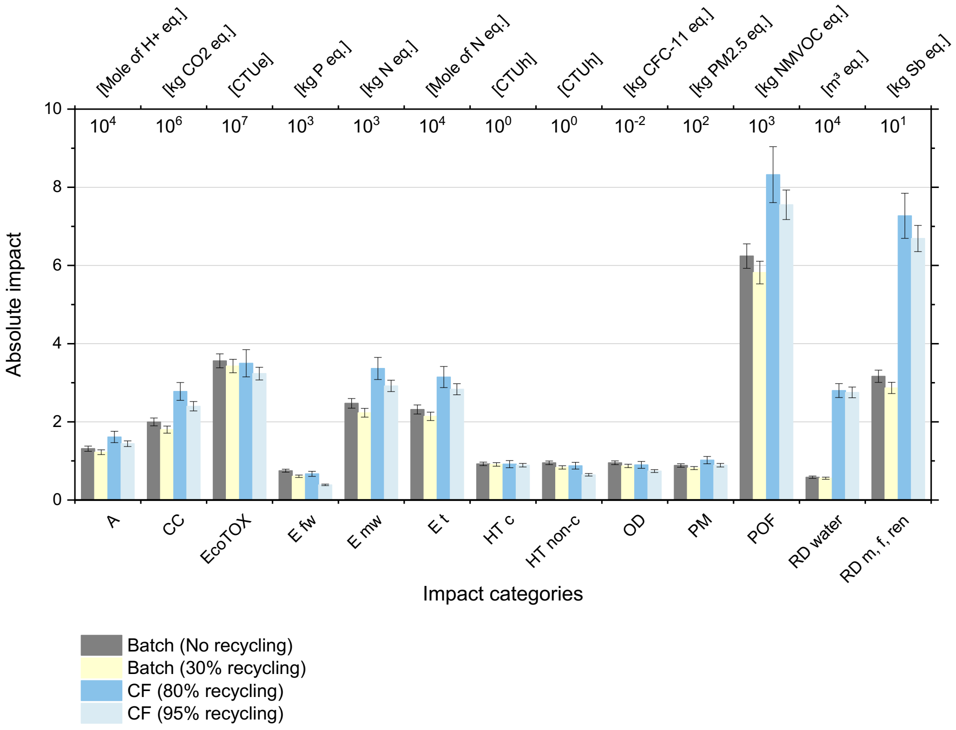


Figure 7.5 - Comparison of the environmental impacts of the batch and continuous flow systems at variable recycling ratios.

In Figure 7.5, four scenarios are considered, each one referring to a different recycling ratio of the ‘mother liquid’ (see Section 7.3.2, ‘System definition’). The results indicate that the environmental impact of the systems is influenced by the recycling ratio. Specifically, lower impacts are achieved with increasing recycling ratios. The recycled stream, ‘mother liquid’, contains large volumes of NaOH that is employed in large quantity in the synthesis. As a result of the recirculation, a lower amount of waste is produced and the use of fresh NaOH is reduced. The latter is used abundantly in the CF system and hence the recirculation system helps mitigating the environmental impacts arising from its production.

Table 7.4 reports the percentage changes of the impact of the CF system with respect to the batch system (scenario: 30% recycling ratio) for each impact category of the analysis.

Table 7.4 - Changes of the environmental impact for the continuous flow production with respect to the batch production.

Impact categories	**% change of environmental impact** with respect to the batch system (30% recycling scenario)	
	CF 80%	CF 95%
Acidification	31%	18%
Climate change	51%	32%
Ecotoxicity freshwater	**2%**	**-6%**
Eutrophication freshwater	9%	-37%
Eutrophication marine	47%	30%
Eutrophication terrestrial	44%	32%
Human toxicity, cancer effects	**1%**	**-2%**
Human toxicity, non-cancer effects	5%	-23%
Ozone depletion	3%	-15%
Particulate matter	25%	9%
Photochemical ozone formation, human health	41%	29%
Resource depletion water	401%	393%
Resource depletion, mineral, fossils and renewables	154%	133%

The results of Table 7.4 need to be read side by side with the results of the normalisation that highlighted the impact categories carrying the majority of the environmental impact of production of zeolite A. In fact, the percentage changes of the impact shown in Table 7.4 have variable importance, depending on how relevant is the impact category in which the change is happening. In other words, the evaluation of the differences between batch and CF production must be based on the impact categories that emerged as primarily relevant in the normalisation, namely, Human Toxicity (cancer effects) and Ecotoxicity of freshwater, and in minor part, Human toxicity (non-cancer effects), Resource depletion (water) and Eutrophication of freshwater.

In Human Toxicity (cancer effects) and Ecotoxicity of freshwater, the CF production has lower environmental impacts than the batch production when the recycling rate is 95%. Specifically, in this scenario, the environmental impact of the CF systems is reduced by -2% and -6% respectively in these impact categories. Even though the percentage reduction of the impact might seem low, it is necessary to recall that Human Toxicity (cancer effects) took 73% of the total environmental impact of the batch system and hence even small reductions translate into significant beneficial effects. When the recycling ratio in the CF system is equal to 80%, the environmental impact in the Human Toxicity (cancer effects) and Ecotoxicity of freshwater are comparable (percentage change with respect to the batch equal to 1% and 2% respectively).

7.4.3 HOTSPOT ANALYSIS

The normalisation and the comparative analyses have identified radical differences in the environmental performances of the batch and CF production systems. This section looks into the causes of these differences by means of a hotspot analysis. The hotspot analysis investigates the single activities that compose the life cycle of the selected production technologies and identifies those activities that contribute the most to the impacts. For simplicity, the role that each activity covered in the production of zeolite A is indicated after the name of the activity, in brackets (e.g. 'NaOH production (Cleaning)', etc.). The results of the hotspot analysis are reported in Figure 7.6.

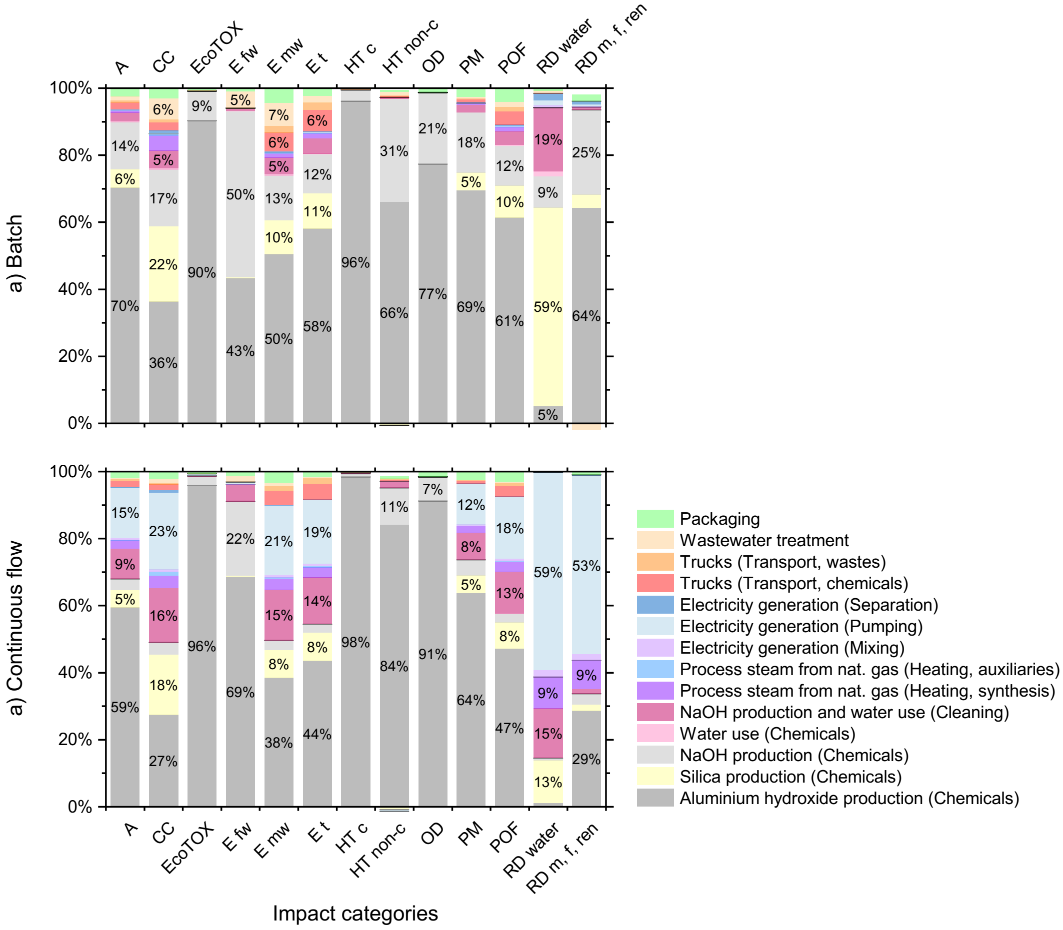


Figure 7.6 - Hotspot analysis for: a) Batch production (30% recycling), b) Continuous flow production (95% recycling).

The production of the chemicals involved in the synthesis of zeolite A take most of the share of the impact of both production systems. Specifically, the production of aluminium hydroxide is the highest contributor compared to the rest of the chemicals, which are mainly silica and sodium hydroxide.

With regard to the production process of aluminium hydroxide, practically all the aluminium hydroxide employed in commercial use is manufactured via the Bayer process[317] which involves dissolving bauxite in sodium hydroxide at high temperatures. The resulting solid waste, bauxite tailings, is removed and aluminium hydroxide is precipitated from the remaining solution of sodium aluminate. The residue (called ‘Red mud’) or bauxite tailings, which is mostly iron oxide, is highly caustic due to residual sodium hydroxide. It was historically stored in lagoons; (this led to the Ajka alumina plant accident in 2010 in Hungary[318,319]). Red mud has a high environmental impact, with primary regards to Ecotoxicity of freshwater and human toxicity (Figure 7.6). The waste was proven to be useful in ceramic production and in building construction. However, the reuse of this waste is still strongly debated in Europe[320]. The US does not approve it due to the dangers it poses to the environment: the EPA identified high levels of arsenic and chromium in some red mud samples[321]. Therefore, the waste is usually disposed in large impoundments, in sort of reservoir created by a dam.

With regard to other chemicals that are involved in the synthesis of zeolite A, NaOH is the other chemical that contributes significantly to the overall impact. NaOH is directly involved in the synthesis and also it is used as cleaning agent. From Figure 7.6a it emerges as a substantial contributor to the overall environmental impact, especially of the batch system. In the CF system, in fact, the weight of its impact over the total impact of the production system is reduced. This is primarily due to the recirculation system, which is more effective in the CF compared to the batch system: this allows the recycling of larger volume of NaOH and consequently reduces the demand of fresh NaOH.

NaOH is also the main source of waste of both production systems. Downstream of the reactor, the synthesis liquid, which is composed predominantly by zeolite A crystals and NaOH, is processed into the separation units. The crystals are recovered and separated from the synthesis liquid, and the resulting stream (‘mother liquid’, composed mainly by NaOH) is consequently disposed. This occurs via truck transport to waste treatment facilities that processes the mother liquid by means of dilution, neutralisation and discharge into lagoons. Evidently, the resulting environmental impact is directly linked to the volume of NaOH present in the waste stream. In fact, the impact of the waste treatment system is detectable in Figure 7.6a for the batch system, whilst being negligible in Figure 7.6b for the CF system, thanks to a better integrated recycling system as explained before.

Finally, the consumption of electricity plays a marginal role in the environmental impact of both production systems. In the CF, however, the resulting impact associated with the production of electricity is slightly higher as a consequence of a pumping system that is more energy demanding. To this end, it is worth remembering that the CF technology hinges on an oscillatory baffled reactor that is powered by a set of pumps controlling the oscillation intensity (frequency and amplitude); thus, the additional energy demand.

Batch and continuous flow systems emerged from the hotspot analysis as having radically different impacts on the environment, with the main differences being in the processing of NaOH and the waste disposal. As a consequence of this, the CF system emerges as a more efficient system. It is worth noting, however, that the majority of the environmental impact of the life cycle of zeolite A is attributable to the production of aluminium hydroxide, a factor in common between both the CF and batch production system. The latter takes up more than 90% of the environmental impact in the impact categories of major relevance, as highlighted in the normalisation analysis, namely Ecotoxicity of freshwater and Human toxicity. Aluminium hydroxide is a building block of the synthesis of zeolite A and the environmental impact of its production is a subject of debate as pointed out before. However, its impact can hardly be lowered by the choice of the production technology and hence, the overall reduction of environmental impact shown by the CF system results contained.

7.5 CONCLUSIONS

We performed a prospective life cycle assessment of the production of zeolite A. Two production technologies were compared, a conventional batch production, used as reference, and an emerging, intensified production technology based on continuous flow. The latter was scaled out conceptually to full scale, starting from an existing pilot plant. The modelling of the life cycle of the two production systems included the production phase as well as all the activities at support of it, such as electricity generation, raw material extraction, and waste treatment.

The results of the assessment indicate that a number of advantages can be gained from the adoption of the continuous-flow technology in place of the conventional batch technology, in terms of environmental impacts. The LCA highlights the importance of adopting a low impacting production system for the manufacturing of zeolite A. This product is, in fact, massively produced worldwide and hence any reduction of the environmental impact of its production would have tangible effects at large scale. This is captured by the normalisation analysis that also identifies the impact categories where the impact of the production of zeolite A is more critical: Human toxicity and Ecotoxicity of freshwater. To this end, the continuous-flow system has a reduced environmental impact compared to the batch system in these highly relevant impact categories. Specifically, the causes of the reduction were investigated through a hotspot analysis and the main ones were found to be a lower demand of fresh NaOH and lower volumes of waste produced, which reflects in a lighter transport system and milder waste treatment.

It is worth underlining that the environmental advantages that have been identified through the assessment of a single production plant of zeolite A would acquire even more robustness in the case that current and future production facilities in Europe adopted the continuous-flow technology in place of the conventional batch technology. However, the LCA suggests that there is a limit to the enhancement that can be made to the current production system: this is represented by the synthesis method itself, in other words the chemicals involved, especially aluminium hydroxide, whose production is responsible for a large portion of the environmental impact of the production system.

In this last case study, the assessment has evidenced the importance of process intensification as an effective way to address and reduce the environmental impact of a process, by enhancing its controllability and containing the generation of wastes. The case of continuous-flow technology applied to the production of zeolite A offers compelling insights about the possibility of a general transition to intensified production technologies, starting from those established processes that still hinge on conventional batch production and that have rooms for improvement but have not yet undergone to a process intensification study. Furthermore, the maturity of the technology and the status of advancement of its development have allowed to compile a robust LCI that translated into having low uncertainties in the calculation of the environmental impacts. As identified in Chapter 3, the efficacy of the framework for the assessment of emerging technologies is contingent on having sufficient data and knowledge on the technology in a relative early phase of the process development. On this note, it is worth recalling the content of Figure 3.1 and Figure 3.2 that underlined how the assessment should be ideally performed at a stage in which it is still possible to intervene in the process development and optimize it towards maximum environmental performances without affecting heavily on the development costs. In other words, the more advanced is the TRL of the target process the higher is the cost of intervening in the process development. To this end, TRL 4-5 (as reported in Chapter 5, 6 and 7) appear to be the sweet spot for the application of the proposed framework.

8 DISCUSSION

During the course of the last decade, the continuous development and evolution of the LCA methodology have revealed a conundrum: the usefulness of LCA is confined to a small segment of the decision-making process that occurs after the technology has been deployed at large scale. The fundamental idea of LCA is to measure and hence contribute to reducing the environmental impacts of a system. However, the conventional way of performing the assessment, namely retrospective or ex-post assessment, is only capable of measuring the impact of an established production technology, but is incapable of intervening during its technology development and hence minimizing environmental impacts. Retrospective LCA in fact cannot guide technology development, as it does not offer a complete understanding of the potential environmental performance of the technology while this is being developed. A consistent portion of the environmental, economic and social impact that a technology or a product have at large scale stems from decisions taken during the early stages of the process development, before it is employed at large scale. These decisions are taken on the basis of the process knowledge that is available at these stages; the latter is incomplete as there is no such standardized and accepted methodology that integrates environmental considerations early in the process development.

In response to this deficiency, new approaches to LCA have been and are currently being developed in order to shift from ex-post assessment to ex-ante or forward looking assessment being able to provide that knowledge on the environmental impact of the technology that is needed before the latter enters the market. By following these premises, it will be possible to anticipate the future impact and intervene in the process development and correct the trajectory in time.

8.1 OBJECTIVE I

Description of the objective (refer to section 1.3 for the list of objectives):

- Review past and current trends in the application of the LCA methodology in order to understand the evolution's trajectory of the methodology
- Identify the main challenges and research gaps in the definition of a prospective LCA methodology and its practical application
- Critically analyze the existing research gaps and derive potential solutions

Key outcome – Notwithstanding the potentialities of forward-looking assessments, the literature review has identified a relevant paucity both in term of available methodologies and, even more, in the practical applications of such methodologies. To this end, the major challenges are:

- Robustness of the life cycle inventory

  The life cycle inventory step is of paramount importance when forecasting the environmental impacts and cost of a technology that is yet to be deployed. Significant uncertainty can in fact be generated in this phase of the LCA; thus, it is required that sufficient data and knowledge on the novel technology is available in order to minimize errors downstream in the LCIA phase. This means that not every system can be subjected to LCA at early stages. To this end, from the literature review it emerges that a large gap exists in the assessment of emerging technologies at lab/pilot scale. The underlying problem is the necessity of having inventorial information on the large-scale setup, which clearly is not available in the nascent phases of the process development. Notwithstanding this, not enough effort has been put into enhancing the LCI at small scales through integration of directly available data with indirect data obtained from scale/up out analysis, thus compensating for the low maturity of the target technology. Rare are the cases in which this happens, and even more rare are the assessments at a pilot scale setup.

- Need of multi-criteria assessment

  LCA methodology is evolving in a direction in which originally external elements such as the economic and social spheres are integrated into the assessment. Multi-criteria evaluation is believed to offer a more robust understanding of the technology under analysis, therefore helping both scientists in the process development and stakeholders in the deployment. It is evident that in last decade a transition has started from LCA oriented solely on the environmental performances to multicriteria evaluation taking into account different aspect of a technology. However, the practical application of multicriteria analysis is still far-fetched. Whilst the economic analysis seems possible, the application of social values into the assessment is far from being perfected.

- Lack of practical examples and comparative analyses

  There exists a general lack of practical examples of LCA of emerging technologies in the literature. Limited are the assessments available for the environmental performance delivered by the application of novel production routes in place of conventionally adopted systems. Specifically, the field of process intensification (PI) offers a great number of promising technologies that call for all-round assessments able to determine in an anticipatory fashion their future environmental and economic performance. To this end, the environmental impacts of novel technologies need to be benchmarked with the state-of-the-art technologies.

8.2 OBJECTIVE II

Description of the objective – presenting a framework for the assessments of emerging technologies, defining an approach to overcome the major challenges identified through the literature analysis and embedding the latter approach into the proposed framework.

Key outcomes – Following up on the main findings of the literature review, the Thesis reported the description of the methodology adopted for the evaluation of emerging technologies. This approach to the assessment started from the main open challenges and lessons learned from the literature review and built upon these a framework for the practical application of LCA at the early stages of the process development.

The proposed framework operationalises the LCA as a tool for: (1) integrating the technology development with environmental and economic inputs, in order to maximise environmental and economic performances of the emerging technology under analysis; (2) helping the decision making process on the deployment of the emerging technology, by benchmarking the projected performances of the latter against conventional production systems at commercial scale.

In order to enable these two functions, the conventional production system is assessed in a retrospective fashion, i.e. following the procedure of a conventional LCA, by assessing the commercial scale system that is already available in the market; the output of the assessment are then used as reference lines on which the environmental and economic performances of the emerging technology are evaluated.

On the other end, the emerging technology is assessed in a prospective fashion. As emerged from the literature the LCI plays a crucial role when forecasting the future performances of a technology. To this end, in the proposed framework, the novel production system under analysis is firstly brought conceptually from lab/pilot scale to the same scale as the reference conventional system. Subsequently, the scaled-up/out system is subjected to assessment. Normalisation and hotspot, and uncertainty analysis are performed in this phase in order to generate the highest level of detail. The output of the assessment is then compared with the result of the LCA on the conventional system. As mentioned before, one of the inherent objectives of the LCA on emerging technologies is to benchmark the future environmental performance of the new technology against one or multiple conventional technologies in order to gain insights into the further developments of these not-yet-introduced technologies and guide upcoming efforts in research and development of the new technology.

To this end, the results of the comparison are sent back as inputs to the process development. The information generated from the comparative analysis comprises quantitative and qualitative information of environmental and economic performances of the emerging technology with respect to the conventional system. Furthermore, by means of the hotspots and normalisation analysis, the inputs carry information on the possible intervention points in the technology development, both in terms of life-cycle phases (e.g. transport, production phase, waste treatment) and in terms of specific activities taking part to the life cycle of the production system (e.g. preparation of precursor, pumping, hazardous waste incineration, etc.). The underlying concept is to enable an "optimisation loop" with process information and projected environmental and economic impacts travelling back and forth between process development and assessment phase, thus contributing to maximising the environmental and economic performances of the emerging technology before the latter enters the market.

A scenario analysis is also performed to capture either the hypothetical impact of replacing conventional systems with the emerging technology, or process conditions under which the latter would bring advantages over conventional systems and hence be deployed.

After having defined the methodological framework for the assessment of emerging technologies, the latter has been applied to four case studies, based on novel production system being developed in academic and industrial R&D and currently at different stages of the process development (TRL 3-5).

8.3 OBJECTIVE III

'Objective III' concerns the application of the framework for the environmental impact assessment of emerging technologies to the selected case studies. 'Objective III' is divided in two subsets: *macro-targets*, which consider a broad perspective and embrace all the case studies, and *micro-targets* that are case-specific.

8.3.1 MACRO-TARGETS

Description of the objective – As per Section 1.3, the subset of *macro-targets* consists in:

- Testing the feasibility of applying the framework at different scales and capturing the possible limitations imposed to the analysis under different TRLs
- investigating how the projection of the environmental impacts vary with different scales

Key outcomes – As reported in case studies in Chapter 4, 5, 6 and 7, the framework for the assessment of emerging technologies has been tested at different TRLs (3-5), hence at different scales that spans from the lab scale to a full pilot scale. The framework was able to produce results for each case study and quantify the uncertainties associated with the different scales.

As anticipated in the conclusions of the literature review, the effect of the scale on the results of the assessment is linked primarily to the robustness of the LCI. In other words, the main limitations are caused by the availability of process data. The data availability depends mainly on the maturity of the process, namely the TRL of the system under consideration; however, the latter is not the only criterion to use when evaluating the applicability of the framework. In fact, the case studies analyzed have revealed that low uncertainties of the results can be achieved at low TRLs, as in the case of the production system of gold nanoparticles of medical application (±10.3% of the environmental impact on average across all the impact categories of the analysis). Notwithstanding the relative low maturity of this process (TRL 4), it was possible to generate a high level of process information as input for the LCI. This was mainly possible because a full PFD was constructed, through a scale up/out analysis, and selecting and sizing - when the information was missing - each operational unit composing a full-scale production. This procedure was enabled by a direct access to the setup and through several iterations of information exchanging with technology developers, thus minimizing the uncertainties of the LCA results normally associated with this scale. The quality of the LCI obtained is comparable to the LCI of the case studies presented Chapter 6 and 7. In these two cases, process data was obtained respectively by means of a collaborative partnership and a secondment period with the two companies (Microinnova and Arkema) currently developing the technologies.

It emerges clearly the sheer importance of having full access to the development of emerging technologies, and collaborating closely with technology developers in order to enable process information and environmental considerations to travel back and forth among the parties involved. To this end, the last case study (production of zeolite A) depicts the ideal situation: the LCI phase undertaken directly on site with full access to the emerging technology - in this case in a pilot plant – and to the conventional production system that was used as benchmark reference.

In the case study III (Chapter 6) – production of Rufinamide – an additional advantage was the possibility to perform the assessment at different TRLs of the same technology. Both the lab scale and the mini-pilot scale were assessed, thus allowing the possibility to factor into the assessment the effect of the scale up/out on the environmental performance of the system under analysis.

In light of the above, the quality of information generated by the LCI phase in the case studies II, III and IV, translated into low uncertainties associated with the projection of the environmental performances of these emerging systems; thus, this enabled advanced considerations on the deployment at large scales of the latter technologies as integration or substitution of conventional production systems. For instance, with regard to the case study IV it was possible to identify under which recirculation efficiencies the novel process would be still able to reduce the environmental impact of the conventional process and hence be deployed. The extents of these considerations are case-specific as reported in the next section (‘*micro-targets*’).

Conversely, in the first case study (CO_2 to formate) the results are confined by the inherent low maturity of the process (TRL 3) which posed an obstacle for deriving a full PFD for the novel process. Due to the low technological maturity of the target system, the outcomes of the assessment are expected to be primarily used as basis to identify the intervention points in the technology development in order to minimize the environmental impacts. In fact, the uncertainties associated with the environmental performance of this novel production system are inherently high (±30.4% on average across all the impact categories) as the process is still far from reaching its final and optimized design. Notwithstanding this, the comparison of the environmental impact of the novel IL production system with the conventional production based on fossil fuel turns helpful to understand the current limitations and the future potentiality of the new technology – as expected and anticipated in Chapter 3.

There is in fact another angle to these conclusions: the higher is the maturity of the emerging technology when the assessment is undertaken, the more costly would be to intervene in the process development to correct the trajectory of the latter and point it towards the maximization of environmental performances (captured in Figure 3.1). Therefore, there exists a tradeoff when selecting the TRL for the application of the framework presented in Chapter 3. To this end, the results obtained in the four case studies suggest that the sweet spot for the application of this methodology is TRL 4-5, which grants the right compromise between having high quality LCI data whilst still being in an early stage of the process development, thus ensuring flexibility for the optimization of the novel system.

8.3.2 MICRO-TARGETS

Description of the objective – the subset of *micro-targets* consists in:

- calculating case-specific environmental performances for each one of the selected technologies; the case studies are subjected to different analyses, i.e. hotspot, normalization, scenario and uncertainty analysis, each one presenting a different angle of the environmental performances of the systems analyzed
- understanding how the results of the environmental impact assessment can be used for providing guidance in the next steps of the process development for each one of the case studies under analysis. In other words, the aim is to identify the potential intervention points in the process development to optimize their performances.

Key outcomes

Formate production from captured CO_2 – The first case explored the possibility to convert CO_2 into valuable chemicals, like formate, which opens compelling opportunities for simultaneously reducing greenhouse gases emissions and resource depletion in chemicals production. This innovative production system – electro-chemical reduction via ionic liquids (ECR-IL) – is currently being developed as part of the EPSRC project on Low Carbon Fuels and is at TRL 3.

The study presented a preliminary overview of the environmental performances of the novel IL production system to understand the potentiality of the latter compared to the conventional production based on fossil fuel. The comparative analysis showed that – as of now – the conventional system is environmentally preferable in the majority of the environmental categories, including climate change. To this end, the assessment has identified a number of intervention points in the technology development in order to minimize the environmental impacts of the novel technology. The hot-spot analysis revealed that the greatest environmental impacts related to the electrochemical conversion process are due to production of electricity used for stirring, to the production of acetonitrile and to the production and disposal of ionic liquid. These impacts are expected to diminish when moving from laboratory to commercial scale. It is crucial to optimize the mixing of the IL synthesis bath and the recirculation of spent IL to reduce the generation of hazardous wastes and avoid incineration of the latter. To this end, future development's steps should be primarily directed at further optimizing these aspects of the ECR-IL system.

Gold nanoparticles for medical applications – Conversely to the first case study, the assessment was performed on a production technology at a more mature stage of the process development. Specifically, it was shown how moving from TRL3 to TRL 4 (bench scale) – thus targeting a system with higher technological maturity - positively affects the construction of the LCI and opens to a wider spectrum of projections and considerations regarding the deployment of the system under analysis.

The assessment outlined that significant advantages can be gained from the adoption of the CF technology in place of the conventional batch technology. In terms of environmental performances, the LCA has evidenced some critical issues in the conventional batch production system, i.e. the production of aggressive compounds used intensively as cleaning agents, and the necessity of resorting to incineration to treat the high volumes of hazardous wastes produced in the synthesis. These factors translate into a high environmental impact that primarily concerns the impact categories of Human Toxicity (cancer effects), Ecotoxicity of freshwater and Resource Depletion (minerals, fossil, renewables), accounting for ca. 83% of the total impact of the batch production system. Furthermore, the study identified that in the scenario in which gold nanoparticles are fully adopted for nano-enabled medical applications in UK, the large-scale deployment of the conventional batch production technology would be unfavourable compared to the CF production. This is primarily evident with regard to Human Toxicity (cancer effects), Ecotoxicity of freshwater and Resource Depletion (minerals, fossil, renewables), in which the CF production system has an environmental impact respectively 95%, 88%, and 10% lower than the batch system. This significant reduction mainly springs from low volumes of hazardous waste generated during the synthesis, as shown in the hotspot analysis. Notably, the CF production system showed a reduction of carcinogenic emissions with respect to the batch system. This is particularly relevant as gold nanoparticles are a product that has the majority of its medical applications in tumour targeting; thus, this severe reduction of the impact avoids the paradox of having a production system that contributes to an increase in cancer cases and hence hampers the effectiveness of its product.

Amongst the chemicals used in the synthesis of gold nanoparticles, the gold precursor ($HAuCl_4$) resulted being the highest contributor to the environmental impact. Its production strongly hinges on gold extraction activities that have the principal consequence of aggravating the depletion of gold resources. The mitigation of the impact of $HAuCl_4$ emerged as a difficult task. Second-hand gold could theoretically be used to manufacture the gold precursor. However, the use of recycled gold would imply a redistribution of gold resources. The redistribution of gold resources would eventually lead to an increase of gold demand in the sector deprived of its resource; thus, resource depletion would be shifted and not reduced. A potential solution might be the recycling of gold nanoparticles after their use, an option that needs further investigation, or complementing gold nanoparticles with alternative nano-products, such as selenides and oxides of Pt and Bi, Gd and Fe.

Rufinamide production – In this case study, an additional step was taken in the dimension scale of the target system. The assessed emerging technology is a continuous flow system currently being tested at a mini-pilot scale (TRL 4.5) for the production of a pharma product. The setup originated from the industrial R&D of Microinnova GmbH, a company that took part to a collaborative partnership with UCL under the EU project ‘COSMIC’ and granted full access to the data on the innovative production system at different scales. Both lab scale and mini-pilot scale setup were investigated in the assessment, and hence consideration on the effect of the scale up were drawn as well as projection on the future deployment of this production technology.

The assessment showed that, under the same overall yield, the CF mini-pilot plant has marginally higher environmental impacts per kg of Rufinamide produced compared to the CF lab system. The mini-pilot plant adopts higher operative temperatures and ratio of reactant-to-precursor that translate into larger quantities of chemicals processed, additional energy consumption, and hence increased effect on the environment. The increase though is marginal and the environmental impact of the CF synthesis of Rufinamide at pilot scale remains significantly lower compared to a conventional batch synthesis. The lower impact stems in large part from the generation of waste, which is effectively mitigated in the CF system. In the latter the E factor is significantly lower than a conventional batch synthesis, and more generally falls below the typical range of E factor values of pharma products. In light of this, it is hence advisable that the CF production technology is adopted in place of the conventional batch synthesis of Rufinamide. However, the last step of the CF synthesis – the cycloaddition – manifested a strong effect on the performances of the mini-pilot plant and hence emerged from the assessment as the key factor for achieving low environmental impacts. Therefore, the next phase of the process development should prioritize the optimization of the cycloaddition step.

Zeolite production – Following up on the previous case studies, the last case study brought on the discussion the application of the framework for the assessment of emerging technologies and moved the discussion on a full pilot scale (TRL 5). The system under analysis originated from the research facilities of Arkema (GRL in Lacq, France) where a CF production system for the production of zeolite A is being developed. The case study was the result of a secondment at the mentioned facilities during which full access to the pilot plant was granted. Furthermore, during the secondment, it was possible to compile a complete LCI on Arkema's current commercial plant based on batch production.

The assessment highlighted the importance of adopting a low impacting production system for the manufacturing of zeolite A. This product is, in fact, massively produced worldwide and hence any reduction of the environmental impact of its production would have tangible effects at large scale. To this end, the continuous-flow system has a reduced environmental impact compared to the batch system in the most relevant impact categories identified in the Normalisation analysis, namely, Human toxicity and Ecotoxicity of freshwater. Specifically, the causes of the reduction were investigated through a hotspot analysis and the main ones were found to be a lower demand of fresh NaOH and lower volumes of waste produced, which reflects in a lighter transport system and milder waste treatment. The assessment indicates that the extent of these advantages depends strongly on the efficiency of the recirculation system of the CF system. The recirculation system is currently being tested for its final integration in the CF systems; the results emphasize the crucial importance of its optimization in the next phases of the technology development in order to deploy a greener alternative to batch production. The novel CF production system emerged from the assessment as capable of reducing the emission of a conventional batch production system, especially in the case that current and future production facilities in Europe adopted the continuous-flow technology in place of the conventional batch technology. However, the LCA suggested that there is a limit to the enhancement that can be made to the current production system: this is represented by the synthesis method itself, in other words the chemicals involved, especially aluminium hydroxide, whose production is responsible for a large portion of the environmental impact of the production system.

8.4 OBJECTIVE IV

Description of the objective – providing an additional criterion of selection and evaluation of emerging technologies by integrating the results of the environmental impact assessment with considerations from the economic sphere.

Key outcomes – The literature review has highlighted the tendency of integrating the environmental impact assessment with considerations pertaining to the economic and social spheres. The aim is to render the LCA analysis more complete, expand its significance, and cover the broader definition of sustainable development that encompasses the environmental, economic and social spheres. Whilst the quantitative assessment of social impacts still lacks general structure and large consensus for its application, the economic assessment can be potentially embedded in the LCA. However, in the case of emerging technologies, this requires having detailed information on operational expenditures (OPEX) and capital expenditures (CAPEX) that are usually not available during the early stages of process development.

To this end, in this Thesis, a particular effort has been put in the compilation of the inventorial information required for the cost assessment. This overlaps with the LCI phase whose quality, as reported in the previous section, is contingent on the TRL of the process as well as on the method of data collection and calculation. More specifically, TRL 4 has been identified as the lower limit of the TRL scale allowing a complete cost assessment that includes OPEX, CAPEX and considerations on the return of investment period.

The case studies have put in evidence that the different R&D environments – academic vs industrial – have a significant effect on the estimation's accuracy of OPEX. In fact, in the case study II (gold nanoparticles production at bench scale), the cost assessment required an extra inventory analysis step for the calculation of bulk prices of the chemicals involved in the synthesis. The technology is currently being developed in an academic R&D and hence it was not possible to rely on chemical prices that are usually negotiated between suppliers and companies. Therefore, the cost of materials and chemicals involved in the synthesis were extrapolated starting from a selection of major chemical suppliers, considering several bulk prices, and interpolating the obtained data points; the resulting trend line was used to extract the price of a given chemical for large bulk orders that are typical of a full-scale system. With regard to the production of gold nanoparticles for medical applications, the cost assessment has shown that economic benefits stem from the adoption of the CF technology in place of the conventional batch technology. The cost assessment revealed that these benefits consist of a notably lower OPEX (-38%) and a shorter payback period for the CF system. The lower OPEX comes from milder cleaning procedures and from the reduction of hazardous wastes produced (-32% in mass). Also, less labour is required compared to the batch system, and this translates into reduced expenses in this respect (-42%), thanks also to a more automated process that enables an online control system and involves no manual cleaning operations.

In the case study III (production of Rufinamide), the LCI included all the necessary data to perform the cost assessment without resorting on assumptions, thanks to a more advanced status of the technology development (TRL 4.5) and to the fact that the technology is developed in an industrial R&D – known chemicals' prices. In this case, the reduction of the cost of the raw materials emerged as the main business driver for the CF synthesis of Rufinamide: 34.2% lower compared to a batch plant with an equal productivity. The cost assessment highlighted the importance of having an optimized yield in a specific step of the synthesis (cycloaddition). This step results having a great impact on the use of raw materials, which take the highest share of the total costs. Additionally, the cost assessment has reported the impact of the uncertainty on the cost estimation for each single raw material. It was observed that one of the chemicals involved in the synthesis, HCl (gas), has the highest impact on potential savings. This indicates the need of an extra step to determine with even more accuracy the oscillation of the final commercial price of this specific raw material. In fact, in the case the actual prices do not deviate greatly from the estimated ones, it could be helpful to take a step back and rethink if HCl (aq.) could be used instead as a mean to reduce costs even further.

With regard to the effect of the scale, the assessment showed that, under the same overall yield, the CF mini-pilot plant has marginally higher costs per kg of Rufinamide produced compared to the CF lab system. The mini-pilot plant adopts higher operative temperatures and ratio of reactant-to-precursor that translate into larger quantities of chemicals processed, additional energy consumption, and hence increased costs. The increase though is marginal and the costs of the CF synthesis of Rufinamide at pilot scale remain significantly lower compared to a conventional batch synthesis. In light of this, it is hence advisable from an economic perspective that the CF production technology is adopted in place of the conventional batch synthesis of Rufinamide. However, the last step of the CF synthesis – the cycloaddition – has a strong effect on the performances of the mini-pilot plant and hence emerges from the assessment as the key factor for generating good return on investment.

On the whole, cost assessments offer the opportunity to extend the scope of the analysis and reach broader conclusions on the sustainability of emerging technologies. The cost assessment should be performed at a scale that minimises the uncertainties associated with the projection of the future costs of the production system once deployed – the scale was identified to be TRL 4-5. From the point of view of the dissemination of the results, it is worth considering that the higher is the advancement status of the process development the higher is the risk of incurring in confidentiality issues. At higher TRLs the assessment can contain confidential information on suppliers and negotiated prices of chemicals and materials involved in the production system; in the case of industrial R&D projects, companies might not be prone to publish this type of information (as in the case of the production of zeolite A – case study IV), regardless of the positive outcomes of the assessment.

8.5 OBJECTIVE V

Description of the objective – reach conclusions on the environmental and economic performances of continuous flow productions compared to traditional batch synthesis, and therefore discuss the environmental and economic implications of a general transition from batch to intensified continuous flow processing as outlined in the EU COMSIC's research goal.

Key outcomes – Chapter 5, 6 and 7 of the Thesis have analysed the performances of three novel production systems based on intensified continuous flow processing. These were benchmarked against conventional batch production systems, with the aim of assessing the feasibility of a transition from conventional batch to intensified continuous flow processing.

A trend has emerged. The assessments have shown evidence that the selected CF technologies have generally lower environmental impact and costs. Specifically, the CF production of gold nanoparticles has shown a reduction of the environmental impacts of -25.1% on average across all the impact categories of the analysis; with regard to the economic performances, the CF production has comparable CAPEX but significantly lower OPEX (-38%) compared to the batch production. The case study III on the production of Rufinamide estimated a reduction of the environmental impact of the CF plant between -55.2% and -73.0% compared to the batch plant; also in this case the main economic benefit of the CF production has been identified in a lower OPEX (-34.2% on average under different recirculation efficiencies). In the last comparison of batch vs CF production – case study IV on the synthesis of zeolite A – the assessment highlighted a reduction of environmental impacts of -4% on average in the most relevant impact categories of the analysis.

Despite all the above mentioned emerging technologies are examples of process intensification applied to the transition from batch to CF processing, it is worth noting that the results of the latter case studies can be generalized only to a certain extent and cannot provide a definitive conclusion to the question posed in ‘Objective V’. This is to say that whilst there are evidences that CF processes have generally better environmental and economic performances for the selected case studies, case-specific assessment are needed for other cases of CF vs batch production. Nevertheless, it is possible to point out with no restrictions that the results of the Thesis are promising signals in favour of the transition from batch to CF processing, from different perspectives:

- The assessment has proven capable of comparing emerging CF technologies against conventional batch technologies; this implies that, for future projects, this approach can be used to assist in time – at the early stages of the process development – the decision-making process of stakeholders regarding funding and investments on emerging CF technologies, as the assessment presents a clear picture of the future performances of these systems.
- Intensified CF processes have shown a series of objective advantages over the batch systems in terms of controllability of the process, autonomation, product quality, online monitoring, generation of waste, easiness of cleaning procedures and recirculation of valuable materials streams. These aspects suggest a technological advancement over batch processing and translates into a tangible enhancement of environmental and economic performances for the selected case studies.
- The above advantages could give an edge to the chemicals’ and advanced materials’ industry in Europe, and hence increase competitiveness in the market. As outlined in the premises of the EU project ‘COSMIC’, the European share of the global chemical market has halved during the period 1996 to 2018 (from ~31% in 1996 to ~17% in 2018) and as a result the number of EU citizens directly employed by this sector has also dramatically fallen (from 1.6 million in 1996 to 1.2 million in 2018). With no doubts one of the main reason behind this fall is the lower-labour-cost markets in the emerging global economies, but equally cardinal motivations have been identified in the lack of technological edge and hence attractiveness to investments[32,33]. To this end, intensified CF technologies emerges as a potential solution to mitigate and counteract this trend. However, despite their potential, relatively few applications have been deployed so far. In Chapter 2, the literature review has highlighted that one of the main reasons for this general paucity is the existence of crucial knowledge gaps in our scientific and engineering understanding of the future impact of these technologies compared to conventional productions. It is of crucial importance to fill this gap of knowledge, and therefore it is recommended to integrate the approach to the assessment proposed in this Thesis in the process development of emerging technologies.

9 CONCLUSIONS

The Thesis presented a potential solution for effectively integrating environmental and economic performance's metrics in the development of emerging technologies.

Despite the growing interest of academic and industrial research, environmental and economic consideration have been seldom included in the early stages of development of new technologies, resulting in non-optimized systems that translate into waste of resources, poor environmental performances and waste of capitals.

As part of the EU ITN program 'COSMIC', the PhD project confronted these challenges and investigated in-depth the feasibility of assessing emerging technologies early in the technology development anticipating future environmental impacts and costs and therefore promoting sustainable processes. The EU program 'COSMIC' assembled together a consortium of leading universities and industry participants with strong background in process intensification, flow chemistry and technology, alternative energy forms and LCA analysis. The consortium envisaged a general transition to intensified processing in the EU chemical and pharma sector, putting sustainability at the center of this transition for the deployment of green and cost-efficient technologies destined at renovating conventional production systems.

Building upon these premises, the Thesis kicked off with an extensive literature review – in Chapter 2 – of the current LCA approaches to the assessment of emerging technologies. This has identified large gaps in the quantification of environmental and economic performances and a worrying lack of operationalisation of the outcomes of these assessments in the process development of novel technologies – this is primarily attributable to the high uncertainties generally associated with conventional LCA approaches to the assessment of emerging technologies.

In response to this deficiency, the Thesis has presented in Chapter 3 a new approach to the assessment of emerging technologies which pragmatically takes into account and overcomes the inherent uncertainties that stems from the low maturity of the systems under analysis and that usually block the assessment or limit the extents of its results.

The proposed framework expanded the area of application of the conventional LCA approach, transforming the analysis into a living process in which process information and projected environmental and economic impacts travel back and forth between process development and assessment phase, hence contributing to maximising the environmental and economic performances of the emerging technology before the latter enters the market. This 'optimisation loop' reduced the typical uncertainties of the LCI linked with low technological maturity, and assured a continuous benchmark of environmental and economic performances with the conventional technologies that the emerging technology considered is meant to integrate/replace.

This approach is new in the field of work of LCA and enables the projection of environmental and economic performances of novel technologies early in the process development. As of now there are no systematic approaches to the assessment of emerging technologies: examples of practical applications are extremely rare and in most of the results of such assessments are compromised by large uncertainties. In light of this, a wide adoption of this approach is expected to have a strong impact on both academic research and industrial R&D activities as it would prevent unexpected environmental impacts and costs during the process development, thus contributing to achieve optimized production systems.

The requirements for rendering this approach possible, however, are demanding especially in the LCI phase of the assessment as it entails having full access to the R&D activities and a continuous direct contact with technology developers.

The Thesis showed that a close cooperation with technology developers, i.e. through industrial secondments or collaborative partnerships, is pivotal to have full access to data and knowledge on the process, and hence have robust LCI for the assessment. To this end, on-site surveys, direct data collection, scale-up/out study, intensive PFD analysis, sizing of peripheral equipment, become part of the LCI to generate high quality inventorial data; this translated into high-fidelity projections of the future performances of the emerging technology and laid the foundation for discussing its eventual deployment at large scale.

Such systematic approach enabled answering all the objectives set in the Thesis, which spanned from outlining case-specific guidelines for the optimization and deployment of the technologies analysed to broader conclusions about the effect of process intensification on the sustainability of production systems and on the transition from batch to continuous flow processing in the chemical industry.

Specifically, in Chapter 4-7, four emerging technologies were assessed at different stages of the technology development (TRL 3-5); in each case study it was possible to quantify for the first time the future environmental performances of such systems in a prospective fashion and integrate the latter with considerations from the economic sphere.

The practical application of the framework has revealed that the LCA on emerging technologies should be performed at a TRL range of 4-5. Chapter 4 has in fact emphasized that whilst it is possible to provide general feedback on the environmental performances of a technology at TRL 3, at this early phase of the process development it is not possible to perform a consistent comparison with conventional technologies, therefore quantifying potential impact savings and reaching robust conclusions on the deployment of the technology. On the other hand, at TRL 4-5, the higher level of maturity assures the right balance between having sufficient data and knowledge on the process but still being in an early phase of the technology development that grants flexibility to process design without implicating high costs. Building upon this, the outcome of these studies was operationalised for the optimisation of the emerging technologies analysed and for outlining the potential environmental and economic savings stemming from their deployment in the market.

Finally, the Thesis posed a question on the environmental and economic implications of a general transition from batch to intensified continuous flow processing in the chemical industry. Chapters 5-7 offered an in-depth comparison on this regard. A trend clearly emerged. The assessments showed evidence that the selected continuous flow technologies have generally lower environmental impacts and OPEX thanks to series of advantages in process' operations. On the whole, the latter analyses showed promising signals in favour of intensified continuous flow systems and open to the possibility of a general process intensification renovation in the chemical industry which could lead to a significant reduction of environmental impacts and operational expenditures, thus rendering the sector more sustainable.

9.1 FUTURE WORK

The practical application of LCA on emerging technologies has provided insights into the optimisation of the selected production systems and the future consequences of their implementation. On this specific note, there are natural follows up that emerged across the Thesis and consist in operationalizing the feedback produced by the assessment into the next phases of the process development of the emerging technologies analysed, such as assessing alternative nanoproducts in the case of gold nanoparticles production, optimizing a specific synthesis step as in the case of Rufinamide production or the recirculation of a material stream in zeolite A production, and investigating more the process design as in the case of formate production.

More generally, future work could focus on expanding the reach of the Thesis and extend the application of the proposed approach to other emerging technologies from academic and industrial R&D. As reported in the previous chapter, it is paramount to produce successful examples of LCA on emerging technologies in order to gather large consensus from both academic and industrial audience and hence build momentum to consolidate this approach in the technology development.

Furthermore, the Thesis has emphasized that the cardinal driver for integrating this type of assessment in the technology development is – in one word – sustainability. In order to render the development of a technology fully sustainable, social impacts could also be factored in.

However, the assessment of social impacts assessment is still an acerb methodology and therefore more effort should be put in this direction.

As final considerations, LCA of emerging technologies offers a chance to structure the collaboration between different actors involved in process innovation. The ultimate goal of this approach is to lie the foundation necessary for debating and guiding research and development, and to provide a solid platform to discuss with all necessary stakeholders involved in the deployment of the technology. Technology developers could apply this type of assessment to explore the potential impacts associated with research decisions, and be engaged in integrating environmental considerations in R&D; as a design tool, LCA of emerging technologies can provide live and timely feedback to technology developers and identify intervention points and potential solutions for the optimization of the technology. Research funders and investors could use LCA of emerging technologies to systematically quantify the potential impacts arising from alternative investment strategies. The set of information that this type of assessment has proven able to generate can complement the current metrics used in the technology development and deployment in order to prioritize investment strategies that maximize environmental performances.

APPENDIX

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COSMIC
EU MSCA-ETN

European Commission
Horizon 2020
European Union funding
for Research & Innovation

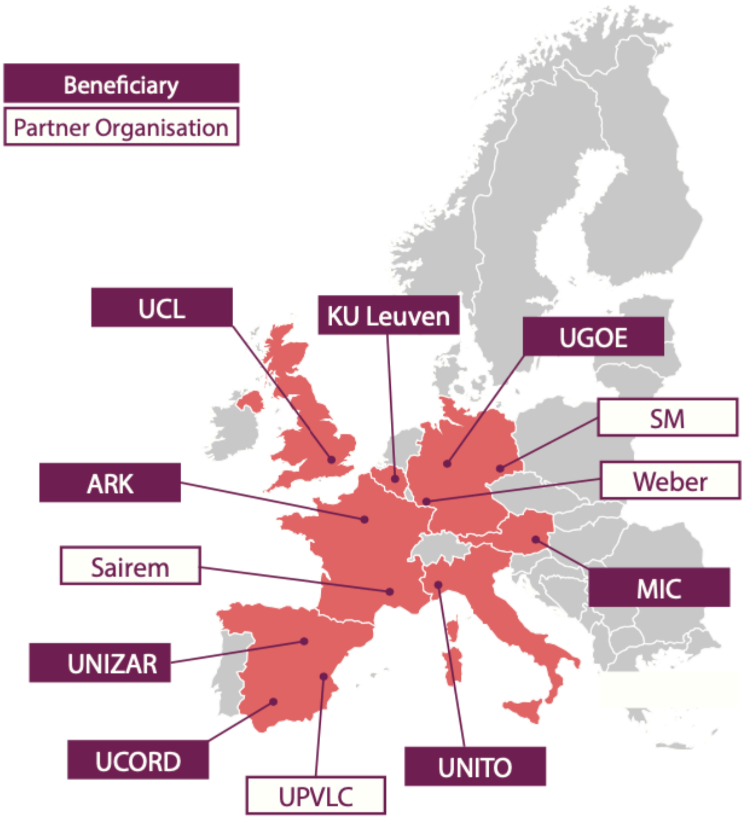

Figure A1 – ‘COSMIC’ consortium (source: EU ITN project description)

The following list reports the Beneficiaries and Partner Organisations of the consortium; the Universities and Industrial partners that took part closely to the projects reported in the PhD Thesis are marked with a star:

Arkema (ARK) *

Georg-August-Universität Göttingen (UGOE)

Katholieke Universiteit Leuven (KU Leuven)

MEAM

Microinnova Engineering GmbH (MIC) *

Sairem

Smart Material GmbH (SM)

Universidad de Córdoba (UCORD)

Universidad de Zaragoza (UNIZAR)

Università degli Studi di Torino (UNITO)

Universitat Politécnica de Valéncia (UPVLC)

University College London (UCL) *

Weber Ultrasonic

Additional Research projects, Organizations and Universities, external to the program ‘COSMIC’, have contributed actively to the research presented in the Thesis. These are:

EPSRC UK*

Low Carbon Fuels Research project*

MaFuMa Research project*

University of Manchester*

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