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Process Design and Sustainable Development—A European Perspective

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Abstract: This paper describes the state of the art and future opportunities for process design and sustainable development. In the Introduction, the main global megatrends and the European Union's response to two of them, the European Green Deal, are presented. The organization of professionals in the field, their conferences, and their publications support the two topics. A brief analysis of the published documents in the two most popular databases shows that the environmental dimension predominates, followed by the economic one, while the social pillar of sustainable development is undervalued. The main design tools for sustainability are described. As an important practical case, the European chemical and process industries are analyzed, and their achievements in sustainable development are highlighted; in particular, their strategies are presented in more detail. The conclusions cover the most urgent future development areas of (i) process industries and carbon capture with utilization or storage; (ii) process analysis, simulation, synthesis, and optimization tools, and (iii) zero waste, circular economy, and resource efficiency. While these developments are essential, more profound changes will be needed in the coming decades, such as shifting away from growth with changes in habits, lifestyles, and business models. Lifelong education for sustainable development will play a very important role in the growth of democracy and happiness instead of consumerism and neoliberalism.

Keywords: process design; sustainable development; chemical industry; process industry; megatrends; design tools

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1. Introduction

In the Introduction, some basic information about process design and sustainable development will be presented, separately for both of them as well as together as process design for the sustainable development era. Then, we shall proceed with the three dimensions of process design—environmental, economic, and social, and continue with process design tools for achieving them. As a case study, the results of sustainable design in chemical, biochemical, and process industries will be presented (process industries include cement, ceramics, food, glass, iron and other metals, oil and gas, plastics, pulp and paper production, waste incineration, etc.), and the article will finish with speculative future development described in the conclusions. However, before going into details, we need to stress the long-term character of process design. Process plants are designed for one or two decades, at least, but most of them operate for several decades. Moreover, process systems will be characterized as circular economy units; they will have to be maintained for longer operation, reused or refurbished for similar future processes, or have its parts and equipment recycled for another process or purpose. Therefore, we need to design for the future. Therefore, it is important to estimate the future development in the company, branch, production, and value chain, in a national and global context. One of the important perspectives is the study of megatrends in the world.

Global megatrends of future development are speculating about our fate: "Trends are an emerging pattern of change likely to impact how we live and work. Megatrends are large, social, economic, political, environmental, or technological changes that are slow to form, but once in place can influence a wide range of activities, processes, and perceptions, possibly for decades. They are the underlying forces that drive change in global markets, and our everyday lives [1].” Although megatrends are not deterministic, they can help us in planning and developing products, processes, and services for future customers. Many studies on megatrends are available, the most popular being the ones of Ernst & Young [2], the European Environment Agency [3] and Pricewaterhouse Coopers [4].

Comparing the most reliable reports on megatrends, some common beliefs can be observed. The following six megatrends and their implications are shown as a synthesis of the four megatrend reports [1–4]:

1. Climate change—(a) Air pollution with greenhouse gases (GHGs) emissions, (b) Exponential climate impacts (extreme weather events acceleration, air–land–oceans heating, polar ice caps, permafrost and glaciers melting, sea-level rise, wildfires, deforestation and deserts), (c) Loss of biodiversity and ecosystem services. Several implications will happen because of the climate change, e.g.,: (i) Decarbonization, reforestation, green buildings, carbon capture with utilization or storage, (ii) Tax on GHGs emissions, (iii) Beyond GDP (gross domestic product) metrics.
2. Resource scarcity—(a) Increased strain on the planet’s resources including degraded soil, (b) Food–water–energy nexus, (c) Critical raw materials. Implications: (i) Zero waste, circular economy and increased efficiency, (ii) Shift from fossil fuels to renewable energy and bio-based raw materials, (iii) Microbiomes (bacteria, archaea, fungi, viruses, and nanoplankton), synthetic biology (intersection of biology and technology).
3. Shifting economic power—(a) Emerging economies (E7—China, India, Brazil, Mexico, Russia, Indonesia, and Turkey) as the growth markets, (b) Global demographics change (different population growth rates), (c) Techno-economic cold war. Implications: (i) Power shift from the west (G7 (Group of Seven)—Canada, France, Germany, Italy, Japan, UK, and USA) to the east (E7), (ii) Industry 4.0 (the fourth industrial revolution, use of cyber-physical systems), (iii) Consumer preferences are changing, e.g., in the food industry (organic and fresh food, online delivery).
4. Technological breakthrough—(a) The pace of change is exponential, not linear, (b) Data are the new oil, (c) Automation and robotization (many jobs will be replaced by machines/robots). Implications: (i) Digitalization—AI (Artificial Intelligence), big data, 3D printing, 5G (the 5th generation) network, IoT (Internet of Things, 26 billion “things” are connected by the internet), (ii) Increased research and innovation, (iii) Industry 5.0 (interaction of human intelligence and cognitive computing).
5. Demographic and social changes—(a) Population continues to grow, (b) More old people and fewer children, (c) Income inequality rises. Implications: (i) Healthcare spending (rise of expenses, saving for retirement), (ii) Education for sustainable development, lifelong learning, creativity, entrepreneurship, (iii) Higher taxation of high incomes and succession duties.
6. Rapid urbanization—(a) Migration to the cities (megacities), (b) Life is better in the cities. Implications: (i) Smart cities, new infrastructure, (ii) Healthcare and security (changing disease burdens and risk of pandemics, crimes and terror—surveillance, monitoring), (iii) Consumer behaviors change (resources will be shared, move from energy suppliers to mobility solutions).

Special studies exploring future trends in different areas exist. Let us mention one of them—New Energy Outlook (NEO) [5], which is forecasting the trends in the energy field, which is one of the most important sources of process industries (see next paragraph). NEO has three major parts: (1) Economic Transition Scenario (ETS), (2) NEO Climate Scenario (NCS), and (3) Implications for Policy. The Executive Summary has six chapters, each one with several scenarios: (a) Energy and emissions, (b) Power, (c) Transport (general, road, shipping, aviation, rail), (d) Buildings, (e) Industry, and (f) Climate.

Industry consumes 29 % of total final energy. Energy consumption grows at an average of 0.6 %/a (per year) and will reach 149 EJ (exajoules, 10^{18} J) by 2050. Steel and chemicals production are the two largest energy consumers in industry, which are responsible for 19 % and 18 % of final energy use in the sector in 2019. They are followed by cement, at 14 %, and aluminium processes, at 6 %. Around 12 % of all fossil fuels consumed in the industry are used as a feedstock for non-energy purposes (from petrochemicals to plastics). In 2050, the sector will account for around 34 % of emissions from fuel combustion, up from 25 % in 2019. Energy demand for steel will grow 50 %, for aluminum will grow 80 %, and for plastics will grow 100 %. High investments in energy—wind 3.3 T$ (trillion US dollars = 10^{12} $) and solar 2.8 T$—are expected by 2050. Prices of renewable wind and solar energy are forecast to fall by about 50 % [6].

1.1. European Green Deal

Process design is and will be increasingly dependent on political decisions in the future. Climate change and loss of biodiversity are an existential threat to Europe and the world. Therefore, the European Commission responded to the first two of the most important risks, mentioned in the above Megatrends, by accepting the European Green Deal (EGD) [7]. It aims to "transform the Union into a modern, resource-efficient and competitive economy where:

- There are no net emissions of greenhouse gases by 2050;
- Economic growth is decoupled from resource use;
- No person and no place are left behind."

The EGD will have a deep influence on life in the European Union, both at personal and enterprise levels. It will also very deeply hit the chemical and process industries.

EU has met its GHG "emissions reduction target for 2020 and has put forward a plan to further cut emissions—at least 55 % by 2030. By 2050, Europe aims to become the world's first climate-neutral continent. Climate action is at the heart of the EGD—an ambitious package of measures ranging from severely cutting greenhouse gas emissions, to investing in cutting-edge research and innovation, to preserving Europe's natural environment. Its action plan aims to:

- Boost the efficient use of resources by moving to a clean, circular economy;
- Restore biodiversity and cut pollution."

One of the first activities is the European Commission's proposal of the European Climate Law, which is a legally binding target of net-zero greenhouse gas emissions by 2050. A system for monitoring progress and taking further action if needed is planned. "Reaching this target will require action by all sectors of the economy, including:

- Investing in environmentally friendly technologies,
- Supporting industry to innovate,
- Rolling out cleaner, cheaper, and healthier forms of private and public transport,
- Decarbonizing the energy sector,
- Ensuring that buildings are more energy-efficient,
- Working with international partners to improve global environmental standards."

EGD and a European COVID-19 response can address Europe's climate, biodiversity, pollution, economic, political and health crises, and at the same time strengthen its institutions and reignite popular support for the European project. SYSTEMIQ and The Club of Rome published a report *A System Change Compass* concentrating on the drivers and pressures that lead to these environmental challenges and on solutions and required changes to the current economic operating model [8]. The report (a) foresees radical resource decoupling and sustainability, (b) offers a system perspective, (c) starts from the human drivers for change, (d) offers a set of principles for support, and (e) takes the natural system as a starting point. To achieve this system-level change, the report addresses three fundamental barriers for the change: (1) shared policy orientations at the overall system level, (2) systemic orientation for each economic ecosystem, and (3) a shared target picture and roadmap for Europe's next industrial backbone.

The System Change Compass offers the following:

- Each of the 10 principles has three orientations giving 30 system-level political orientations for the overarching system as a checklist for policymakers;
- Eight ecosystem and three to five ecosystem orientations (directions) for Europe's industrial backbone;
- Over 50 Champion orientations (directives) that form a view of industrial priorities.

The 10 principles with their orientations are including the following redefinitions:

1. Prosperity—from economic growth to fair and social economics;
2. Natural resources—consumption and development decoupled, a shift to responsible usage;
3. Progress—from economic activities/sectors to societal needs within planetary boundaries;
4. Metrics—from GDP growth to natural capital and social indicators;
5. Competitiveness—EU based on low-carbon products, services, and digital optimization;
6. Incentives—aligned with the Green Deal ambitions and economic ecosystems;
7. Consumption—from individual identity to an individual, shared, and collective identity;
8. Finance—from subsidizing "old" industries to supporting economic ecosystems;
9. Governance—from top–down to transparent, flexible, inclusive participatory one;
10. Leadership—from traditional to system one, based on an intergenerational agreement.

The eight economic ecosystems with over 50 Champions are resulting in industrial priorities:

1. Healthy food (organic, no waste, water, urban agriculture, alternative proteins, etc.);
2. Built environment (planning, ownership, buildings repurpose and retrofit, net zero, circular);
3. Intermodal mobility (high-speed railways, green aviation and shipping, ride-sharing, etc.):
4. Consumer goods (product–service, product sharing, maintenance, and value retention);
5. Nature-based (degraded land restoration, urban greening, ecotourism, paid ecosystem services, forest, sea, marine, and land protection);
6. Energy (renewables, hydrogen, low-carbon fuels, smart metering, carbon capture, grids);
7. Circular materials (value chain systems, asset recovery, and reverse logistics, markets for secondary materials, high-value material recycling, materials-service, 3D printing, etc.);
8. Information and processing (distributed manufacturing, high-speed infrastructure, etc.).

1.2. Process Design

Process Design (PD) is the choice and sequencing of processing steps and their interconnections for desired physical and/or chemical transformation of materials [9]. The steps include several unit operations: reaction, separation, mixing, heating, cooling, pressure change, particle size reduction or enlargement, etc. Today, the design is governed by the circular economy, which requires design for repair, reuse, recovery, refurbishment, restoration, and recycling [10]. Process design is distinct from equipment design, which is closer to the design of unit operations. Process design can be the design of new facilities or it can be the modification or expansion of existing ones. The process design can be divided into three basic steps: synthesis, analysis, and optimization [11].

Design starts with process synthesis—the choice of technology and combinations of industrial units to achieve goals. First, product purities, yields, and throughput rates shall be defined. Modeling and simulation software is often used by design engineers. Simulations can identify weaknesses in a design and allow engineers to choose better alternatives. However, engineers still rely on heuristics, intuition, and experience when designing a process. Human creativity is an important element in complex designs.

Process analysis is usually made up of three steps: solving energy and material balances, sizing and costing the equipment, and evaluating the economic worth, safety, operability, etc. of the chosen flow sheet.

Optimization involves both structural and parametric optimization. Structural optimization is more difficult, and it includes equipment selection and interconnection between the units. Parameter optimization is regarding stream compositions and operating conditions such as temperature and pressure.

Several decisions have to be made during the design of each process while respecting the aforementioned objectives: i.e., constraints (capital investment), social conditions (employment, health and safety), environmental impacts (emissions, waste, resource efficiency, operating and maintenance costs), and other factors such as reliability, redundancy, flexibility, and variability in feedstock and product. Process design documentation includes the following:

- Simple block flow diagrams (BFD, rectangles and lines indicating major material or energy flows, stream compositions, and stream and equipment pressures and temperatures),
- More complex process flow diagrams (PFD) or process flowsheets with major unit operations, material and energy balances,
- Piping and instrumentation diagrams (P&ID, piping class, pipe size, valves and process control schemes), and specifications (written design requirements of all major equipment items).

Working Party of the European Federation of Chemical Engineering (EFCE) on Computer-Aided Process Engineering (CAPE) is organizing annual events—the European Symposium on Computer-Aided Process Engineering (ESCAPE) in which researchers and practitioners in the field of computer-aided process systems engineering from academia and industry come together. Process engineering focuses on the design, operation, control, optimization, and intensification of chemical, physical, and biological processes from a vast range of industries: agriculture, automotive, biotechnical, chemical, food, material development, mining, nuclear, petrochemical, pharmaceutical, and software development. The application of systematic computer-based methods to process engineering is called "process systems engineering". Papers presented at the ESCAPE events are all published in Elsevier publications, the CAPE Proceedings Series *Computer-Aided Chemical Engineering* [12].

In the United States of America (US), a nonprofit organization CACHE (Computer Aids for Chemical Engineering) organizes the Foundations of Computer-Aided Process Design (FOCAPD) international conferences, focusing exclusively on the fundamentals and applications of computer-aided design for the process industries. The conference is organized every five years and brings together researchers, educators, and practitioners to identify new challenges and opportunities for process and product design. Papers from the conferences are published by the Elsevier CAPE Book series as *Proceedings of the International Conference on Foundations of Computer-Aided Process Design*.

1.3. Sustainable Development

Sustainable development (SD) must meet the needs of the present without compromising the ability of future generations to meet their own needs [13]. The Amsterdam Treaty of European Union (EU) sets out the EU "vision for a sustainable development of Europe based on balanced economic growth and price stability, a highly competitive social market economy, aiming at full employment and social progress, and a high level of protection and improvement of the quality of the environment." Transforming our World: the 2030 Agenda for Sustainable Development, including its 17 Sustainable Development Goals (SDGs) and 169 targets, was adopted in 2015 by Heads of State and Government at a special United Nations (UN) summit. The Agenda is a commitment to eradicate poverty and achieve sustainable deveopment by 2030 worldwide.

The Chemical Sector SDG Roadmap is an "initiative led by a selection of leading chemical companies and industry associations, convened by the World Business Council for Sustainable Development (WBCSD), to explore, articulate, and help realize the potential of the chemical sector to leverage its influence and innovation to contribute to the SDG agenda" [14]. Building on the Responsible Care program and other sustainability initiatives, "the European Chemical Industry Council (Cefic) and its members have developed a Sustainability Charter and agreed on a roadmap to foster innovation" [15]. They focused on resources in the "four critical areas to progress sustainable development: low-carbon economy, resource efficiency, circular economy and human protection".

The International Conference on Sustainable Development (ICSD) is organized annually by the European Center of Sustainable Development (ECSD) in collaboration with other partners; conference papers are published in the open-access European Journal of Sustainable Development, issued by the ECSD [16]. Conference proceedings are good sources of recent research and development in the area.

The American Institute of Chemical Engineers (AIChE) and the Association of Pacific Rim Universities (APRU, a network of leading universities linking the Americas, Asia, and Australasia) have organized the Conference on Engineering Sustainable Development in December 2019 [17]. They are going to organize the 2nd Engineering Sustainable Development Conference in December 2020, both conferences addressing the UN 2030 Agenda for Sustainable Development and the 17 SDGs.

The Asia Pacific Institute of Science and Engineering (APISE) is organizing International Conferences on Environmental Engineering and Sustainable Development (CEESD) annually; papers are published in the IOP (Institute of Physics) Conference Series: Earth and Environmental Science.

1.4. Process Design and Sustainable Development

Process Design and Sustainable Development (PD&SD) started with the ecodesign (ecological design, also called green design or environmentally conscious design), which considered the environmental impact of a product throughout its entire life cycle only. A typical example is green engineering design [18], which evolved from the green chemistry principles [19]. As sustainable development (SD) has also economic and social components, the additional SD principles have been integrated into engineering design [20]. Today, sustainable development is a part of engineering principles [21,22].

Crul and Diehl published a handbook on Design for Sustainability (D4S) [23]. Ceschin described the evolution of design for sustainability [24] and Acaroglu overviewed sustainable design strategies [25]. The generic conventional engineering design process is including four phases: (1) planning and problem definition, (2) conceptual analysis, (3) preliminary design, and (4) detailed design [12].

Many textbooks on chemical process design are on the market. An older one is dealing with preliminary analysis and evaluation of processes, the analysis using rigorous models, and basic concepts in process synthesis with optimization approaches [26]. Economic evaluation is dealt with, heat and power integration are described to reduce energy consumption, and safety is the only social topic mentioned. In some textbooks, sustainable development and environmentally sound design (prevent/minimize, recycle/reuse, and recovery) are also described using a few pages [27]. More recent ones are adding process intensification, steam system and cogeneration, environmental design for atmospheric emissions, water systems, and clean process technology, as well as inherent safety chapters [28].

Professional literature on PD&SD was more advanced in the past decades, as design engineers had to respect laws and regulations regarding environmental protection, labor protection, and occupational safety in the approval procedures [29]. Newer literature is including natural resource and environmental challenges, sustainable materials identification, sustainability improvements of engineering designs, evaluation of sustainable designs, and monetizing their benefits besides the legislative framework [30]. A sustainability engineering approach is also including Total Quality Management [31] and Life-Cycle Assessment (LCA) [32].

2. Process Design for Sustainability

The publication statistics search in Scopus [33] includes article titles, abstracts, and keywords. It contains an abstract and citation database with over 25 100 titles (articles, conference papers, books, etc.). Searching for the four words: process, design, sustainable, and development yielded 16 135 documents, 2 869 of them in open access. There was a constant rise in the number of publications since the year 1999 (54 documents), reaching 1 859 documents in 2019. By subject area, most of them belong to Engineering (7 060) and Environmental Science (4 090); they are followed by Energy (2 848), Social Sciences (2 777), and Computer Science (2 471). Of these, 7 487 of them are articles, 6 330 are conference papers, 1 085 are reviews, 703 are book chapters, and 294 are conference reviews. Most of the articles were published in J. Cleaner Production (456) and in Sustainability journal (290). The authors with the most publications are still coming from the EU and USA; the most frequent affiliations are located in EU and China: Delft University (170), Politecnico di Milano (123), Wageningen University & Research (114), Danmarks Tekniske Universitet (108), and Chinese Academy of Sciences (99). The most frequent keywords are sustainable development (9 604) and sustainability (2 512), followed by design (1 840), product design (1 511), and life cycle (1 514); process design is not so often mentioned.

Similar statistics in the Web of Science (WoS) Core Collection database [34] showed 8 915 documents (14 823 in WoS All Databases); a steady growth was realized in the last four years—from 772 units in 2016 to 1 234 ones in 2019. Most of them (2 557) belong to the categories of environmental science and studies, 1 528 belong to green sustainable science and technology, 808 belong to environmental engineering, and 620 belong to energy and fuels. Articles (5 610) are prevailing, followed by papers in proceedings (2 700), reviews (818), and book chapters (260). Regarding the organizations, Wageningen University Research (102), Delft University of Technology (98), Centre National de la Recherche Scientifique (89), Helmholtz Association (88), and Chinese Academy of Sciences (86) are on the top.

The WoS Core Collection base covers more than 21 419 journals, books, and conference proceedings, while the Web of Science platform includes 34 586 journals, books, proceedings, patents, and datasets. As it was impossible to review several thousand documents, the highly cited ones in the field (121 documents) were selected. Examining their titles lead to 43 documents, and by reading their abstracts, 16 articles were selected for a closer look.

2.1. Environmental Dimension

Most of the selected 16 articles deal with environmental sustainability; however, the economic dimension is included in only nine of them—mainly as a criterion for process optimization. The social dimension (health) is present in two of them. Optimal design of chemical processes and supply chains is concentrated on energy efficiency as well as waste and water management [35]. Multiple criteria decision making (MCDM) [36] and Life-Cycle Assessment (LCA) [37] are the tools most often mentioned. Various metrics are used to assess the sustainability of processes; the three most popular ones are presented here:

- United States Environmental Protection Agency's (EPA) "Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a multi-Objective Process Evaluator (GREENSCOPE [38]) tool provides scores for the selected indicators in the economic, material efficiency, environmental and energy areas having about 140 indicators in four main areas: material efficiency (26), energy (14), economics (33) and environment (66)";
- The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2.0 [39]) "for sustainability metrics, life-cycle impact assessment, industrial ecology, and process design impact assessment for developing increasingly sustainable products, processes, facilities, companies, and communities"; it is containing human health criteria-related effects, too; and
- The mass-based green chemistry metrics, extended to the "environmental impact of waste, such as LCA, and metrics for assessing the economic viability of products" and processes [31].

Sustainability-oriented innovations (SOIs) in small and medium-sized enterprises (SMEs) are integrating ecological and social aspects into products, processes, and organizational structures [40].

Five out of the 16 articles dealt with biofuels. Purified biogas is an essential source of renewable energy that can act as a substitute for fossil fuels; anaerobic co-digestion is a pragmatic method to resolve the difficulties related to substrate properties and system optimization in single-substrate digestion processes [41]. The synthesis of important biofuels using biomass gasification, key generation pathways for their production, the conversion of syngas to transportation fuels together with process design and integration, socio-environmental impacts of biofuel generation, LCA, and ethical issues were discussed [42]. A multi-objective possibilistic programming model was used to design a second-generation biodiesel supply chain network under risk; the proposed model minimized the total costs of biodiesel supply chain from feedstock supply to customers besides minimizing the environmental impact [43]. The cultivation, harvesting, and processing of microalgae for second-generation biodiesel production, including the design of microalgae production units (photo-bioreactors and open ponds) was described [44]. A multi-objective optimization model based on a mathematical programming formulation for the optimal planning of a biorefinery was developed, considering the optimal selection of feedstock, processing technology, and a set of products [45].

Circular economy topics are the second most numerous ones within 16 articles. The first one traced the conceptualizations and origins of the Circular Economy (CE), researched its meanings, explored its antecedents in economics and ecology, and discussed how the CE was operationalized in business and policy [46]; the authors proposed a revised definition of the CE to include the social dimension. Another contribution proposed a new unified concept of Circular Integration that combined elements from Process Integration, Industrial Ecology, and Circular Economy into a multi-dimensional, multi-scale approach to minimize resource and energy consumption [47].

High-pressure technologies involving sub- and supercritical fluids offer a possibility to obtain new products with special characteristics or to design new processes that are environmentally friendly and sustainable [48]. Sustainable product–service systems offer service by lending the product to a customer—they attempt to create designs that are sustainable in terms of environmental burden and resource use whilst developing product concepts as parts of sustainable whole systems that provide a service or function to meet essential needs [49].

2.2. Economic Dimension

For most managers in industry, economic performance is the most important criterion for decisions on investing money in production and energy facilities [50]. Economic performance indicators are well known, and process and product designs are usually carried out by maximizing profits or minimizing costs [51]. Other criteria are used less frequently, e.g., the network for the conversion of waste materials into useful products has been optimized using the maximum return on investment [52].

Techno-economic evaluations of process alternatives with different criteria lead in some cases to the same best solution, as Ziyai et al. [53] showed by comparing the three biodiesel production scenarios with the criteria net present value, internal rate of return, payback period, discounted payback period, and return on investment. In general, optimization using different economic criteria leads to different optimal process solutions [54]. These processes differ not only in economic performance but also in operational efficiency and environmental impact [55]. This phenomenon is particularly evident in more precise mathematical models [56], which include sufficient trade-offs between investments on one hand and benefits on the other, such as higher conversion, higher product purity, the higher degree of heat integration between process streams. Applying the correct economic criteria can lead to more sustainable solutions; for example, the net present value criterion provides optimal process solutions that strike a balance between long-term stable cash flow generation, moderate profitability, and moderate environmental impact [57].

With the introduction of the concept of sustainable development, criteria other than economic indicators have become more important in process design, thereby promoting the reduction of negative environmental impacts and the improvement of social performance. When designing sustainable processes, the techno-economic, environmental, and social criteria of various process alternatives are evaluated and the most suitable solution is selected from among them, whereby compromises between all criteria are sought [58]. More systematic approaches use multi-objective optimization. The most common method is to generate equivalent non-dominant Pareto solutions that show a range of solutions where the improvement of one criterion leads to the deterioration of other criteria [59]. However, Pareto curves are not best suited for decision making, because the decision-maker usually must choose one alternative for realization, which requires additional multi-criteria analyses of Pareto solutions [60].

Another approach is to transform the multi-objective optimization into a single-criterion optimization by monetarizing all pillars of sustainability, which means that in addition to the economic criterion, environmental and social impacts are also expressed in monetary terms. However, this is not an easy task, as environmental and especially social impacts cannot simply be expressed in monetary terms. Environmental impacts are expressed in terms of the burdens and reliefs of the environment. They can be monetized using the eco-cost system [61], which expresses the cost of environmental pollution at the price necessary to prevent it. Greenhouse gas emissions can be monetized with a CO_2 tax. Novak Pintarič et al. [62] showed that a deviation from the economic optimum for investments in emission-reducing technologies can lead to a reduction of the tax due to lower emissions, which can compensate for economic loss to a certain extent. The point on the Pareto curve was called the "Economic–Environmental Break Even".

Sustainable process designs include various concepts to achieve sustainable solutions; examples are cleaner production [63], zero waste processes [64], zero carbon emission technologies [65], LCA environmental impact assessment in early design phases [66], eco-efficiency indicators [67], etc. Recently, the concept of the circular economy has become particularly popular and sometimes even overcomes the term sustainable development, although the terms are by no means equivalent [68]. The concept of circularity is already being used in the design and optimization of technologies and processes, such as the recovery of hydrogen from industrial waste gases [69] or the development of the novel indicator Plastic Waste Footprint to facilitate an improvement of circularity in the use of plastics [70].

Process systems engineering offers many approaches and tools for the design of process solutions in the field of circular economy and sustainable development, such as the synthesis of processes and supply chains with mathematical programming, process integration, optimization and intensification, multi-objective and multi-level optimization, optimization under uncertainty conditions, etc. [71]. The fact is that circular economy projects, especially those that solve the waste problem, are hardly economically successful based on classic economic criteria; for example, recycling of plastics is not economically viable at low fractions of recycled material [72]. However, it is important to look at these projects in a broader perspective and to include all the three dimensions of sustainable development into design and strategic decision-making.

2.3. Social Dimension

In process design, economic and social dimensions are important in addition to environmental performance. To achieve a sustainable and circular economy, it is necessary to develop all the three pillars of sustainable development as well as SDGs and take them into account in process design. While economic and environmental aspects are well established and quantified, social criteria are far less developed. The integration of social effects into process design is difficult, and little research has been conducted, although it is becoming increasingly important in both the academic and business environments [73]. The monetization of all the three pillars of sustainable development has been used to synthesize processes and supply networks with sustainability criteria such as sustainable profit [74] and sustainable net present value [75].

Each company has to take care of their customers, employees, owners or shareholders, and local community to fulfill their requirements. Companies shall respect the corporate social responsibility standard, ISO 26000 [76]; the standard is voluntary, and it is based on the following:

(a) Seven key principles: accountability, transparency, ethical behavior, respect for stakeholder interests, respect for the rule of law, respect for international norms of behavior, and respect for human rights;
(b) Seven core subjects: organizational governance, human rights, labor practices, the environment, fair operating practices, consumer issues, and community involvement and development.

What can a process designer do in this respect?

Regarding the employees, it is the most important to design a process, its equipment, and products in the way that enables safety and health protection at work (occupational health and safety, OHS) [77]. It is including the physical, mental, and social wellbeing of workers. OHS is achieved by using process monitoring and control, automation, even robots to prevent contact with dangerous substances, fires and explosions, accidents at work, release heavy burdens, etc. Digitalization and computer-aided operation of plants are used increasingly to release the workers from process malfunctions, unexpected events, or even accidents.

Similar requirements are valid for customers using products of the process industries. This is particularly important for chemicals, which can have negative effects on customers' health, safety and wellbeing. The products shall be long-lasting, without weak elements, easy to maintain, and user friendly. Product design is critical for its dismantling and recycling at the end of life. Take back or product–service systems are used increasingly to enable circular economy with the reuse of materials and energy in the waste products. Every designer shall use Life-Cycle Assessment (LCA) methodology [78] to evaluate impacts throughout the supply chain, from raw materials extraction to processing, use, and end-of-life treatment, applying the principles of the circular economy.

The local community is strongly connected with processes and operation of the company located within its boundaries. Most employees are coming from the neighborhood, and employment is enabling their families to live better. The local population is very sensitive to any radiation and emissions into the air, water, or land around the factory. Process design has to take care of their health and safety by proper process design as well as by planning sensors, monitoring, and measurement units in the surroundings of the company buildings. Often, the process of surplus heat can be used for heating public buildings or even residents' houses. Zero-waste, wastewater treatment and reuse, and hazardous waste recycling are important principles guiding process design. The selection and monitoring of indicators shall be carried out well in advance, during the process design.

Most of the companies are using the Global Reporting Initiative (GRI) to communicate their impacts on people (human rights, corruption, etc.) and the planet [79]. GRI's framework for sustainability reporting helps companies identify, collect, and report their impacts in a clear way.

2.4. Process Design Tools and Sustainability

The Process Systems Engineering (PSE) Community has fully embraced the concept of "sustainability" as one of the leading guides in process design. Although it is difficult to pinpoint the exact time when the three pillars of sustainability (i.e., economic, environmental, and social) were considered and emphasized simultaneously in the design of chemical processes, one may argue that even the works published as early as the late 1970s [80] and early 1980s [81] directly addressed at least two of the pillars of sustainable process design—economic and environmental ones. Although the incentives to develop what we now regard as a sustainable process may have been purely economic at the time, the enabling insight was the ability to view a chemical process as a system—the system that is not isolated from its environment, but a system that interacts with the environment.

Fast-forward five decades of research in the field of PSE, the approaches to designing sustainable chemical processes rely heavily on computer-aided tools. These tools enable simulation, analysis, optimization, and synthesis of chemical processes at various spatial and time scales. They range from computer-aided molecular design [82], simulations of transport phenomena (heat and mass transfer in single or multiphase flows) [83], simulations of single-unit operations [84] and whole processes [85] to the synthesis and optimization of processes [86,87] and complete supply networks [88]. The widely accepted approach to assess the sustainability of a given process design is the Life-Cycle Sustainability Assessment (LCSA), which is commonly performed to compare different process design alternatives [89] after the feasible designs have been identified. On the flip side, if a composite sustainability criterion, for example, the sustainability profit [90], is incorporated directly into the process synthesis and optimization phase as an objective function, the most sustainable designs can be obtained directly without the need of a posteriori LCSA assessment.

The PSE computational tools enable a practical way to analyze the performance of a wide range of product–process engineering problems as well as to identify the possibilities for improvement However, some software packages come together with a high license price, and although the price can be justified with the benefits gained, it very often remains an obstacle, especially for small engineering companies. However, in the last few years, the open-source initiatives have begun to offer freely available alternatives to the paid versions (Table 1). Provided that quality matches those of their paid counterparts, a greater adaptation of these tools in the industry can be expected.

Table 1. Licensed and free computational tools, used for process simulation, synthesis/optimization, and sustainability assessment.

Software	Description	Web Site	License
ANSYS Fluent [91]	Computational Fluid Dynamics	www.ansys.com	Licensed
OpenFoam [92]	Computational Fluid Dynamics	www.openfoam.com	Free
Aspen Plus [93]	Process Simulation	www.aspentech.com	Licensed
DWSIM [94]	Process Simulation	dwsim.inforside.com.br	Free
GAMS [95]	Mathematical programming and optimization	www.gams.com	Licensed
Pyomo [96]	Mathematical programming and optimization	www.pyomo.org	Free
GABY [97]	LCA and sustainability assessment	www.gabi-software.com	Licensed
OpenLCA [98]	LCA and sustainability assessment	www.openlca.org	Free

Identifying what could generally be considered as mitigating solutions to complex problems is necessary, although such solutions may not be sufficient to achieve the goals of sustainable development in the long term. A real breakthrough will be achieved by identifying innovative restorative solutions. In this context, the Process Systems Engineering (PSE) should develop tools that simultaneously address the whole (bio)-chemical supply network. To harvest the synergistic effects among the constituents of the supply network to a greater extent, the traditional (bio)-chemical supply network should be expanded to include additional elements (e.g., nano-robots, molecular machines, labs-on-chips, or micro-processes) and linked to other supply networks (energy, agriculture, food, etc.) to form circular and sustainable system-wide supply networks.

Despite many achievements and contributions of the PSE community that undeniably contributed to the development of the modern biochemical and chemical industry, there are no professional tools and hardly any academic ones that are specialized in providing innovative solutions to these complex problems.

A noteworthy initiative to develop an advanced computer platform to support innovative conceptual design and process intensification is the IDEAS PSE Framework [99]. The platform addresses the capability gap between state-of-the-art simulation packages and algebraic modeling languages (AMLs) by integrating an extensible, equation-oriented process model library within the open-source Pyomo AML, which addresses challenges in formulating, manipulating, and solving large, complex, structured optimization problems.

The second initiative is MIPSYN-GLOBAL [100]. It is being built on the foundations of its predecessor MIPSYN [101], making use of knowledge and experience gained in the decades of research in the field of PSE. The development of MIPSYN-Global encompasses all the four basic PSE tasks: (i) development of advanced synthesis concepts, algorithms, and strategies; (ii) modeling; (iii) development of synthesizer tools; and (iv) development of different applications.

3. Case Study

The European Union (EU) is the second-largest chemicals producer in the world—with 565 M€ (million euros), it is behind China (1 198 M€) but before NAFTA (North American Free Trade Agreement—USA and Canada, 530 M€); EU a positive trade balance [102]. About 96 % of all manufactured goods rely on chemistry. The chemical industry is the fourth-largest producer after automotive, food, and machinery/equipment ones; with the 16 % added value, it is the leading sector in the EU. A total of 29 000 small, medium, and large companies are offering 1.2 million jobs, which is 12 % of EU manufacturing employment. Labor productivity in chemicals is 77 % higher than the manufacturing average, and salaries are 50 % higher. It is also the largest investor in EU manufacturing. The chemical industry is spending 10 G€/a (billion euros per year) for research and innovation.

3.1. European Chemical Industry Council

The European Chemical Industry Council (Cefic) is the European association for the chemical industry. Cefic developed the Sustainable Development Vision in 2012. It was based on the Responsible Care program—a global, voluntary initiative developed autonomously by the chemical industry. It was initiated by the Canadian Chemical Producers' Association—CCPA in 1985, and it is now adopted by almost 90 % of the global chemical industry. It aimed to improve health, safety, and environmental performance. Cefic's Sustainable Development program started in 2016; it aims at the transition toward a safe, resource-efficient, circular, and low-carbon society. It is organized around the four sustainability focus areas of the Cefic Charter: Create Low-Carbon Economy, Conserve Resource Efficiency, Connect Circular Economy, and Care for People and Planet [103]:

- Enabling the transition to a low carbon economy by:
  - Promoting innovation and stimulation of breakthrough technologies development in energy-efficient chemicals processes,
  - Offering market solutions consistent with low-carbon requirements,
  - Fostering the development and use of sustainable and renewable raw materials,
  - Fostering the use of sustainable and renewable energy and raw materials with a focus on cost and accessibility,
  - Innovating for chemical energy storage, and
  - Developing fuels and building blocks built on CO_2;
- Driving resource efficiency across global value chains and their operations by:
  - Designing sustainable solutions needing fewer resources over the entire life cycle and allowing easy reuse and recycling,
  - Maximizing material recovery and reuse,
- Promoting the adoption of circular economy principles to prevent waste, achieve low-carbon economy, and enhance resource efficiency;
- Preventing harm to humans and the environment throughout the entire life cycle by:
  - Mitigating risks, including assessment of substitutes,
  - Promoting the uptake of safe substances, materials, and solutions,
  - Minimizing negative environmental impacts on biodiversity and ecosystems,
  - Facilitating reuse, recycling, and recovery with steady information flows on products.

In the period 1991–2017, chemical production rose by 84 % while energy consumption was reduced by 16 % and energy intensity was reduced by 54 % (–40 % in the whole industry) [102]. Fuel and energy consumption was reduced by 24 % in the same period. In the period 1990–2017, greenhouse gas (GHG) emissions have been reduced by 58 % or 190 Mt/a, from 330 Mt/a down to 160 Mt/a of CO_2 equivalent. GHG emissions per energy consumption have been reduced by 48 %, and GHG intensity per production was reduced by 76 %. In the period 2007–2017, acidifying emission intensity fell by 40 %, nitrogen emission intensity fell by 48 %, and non-methane volatile organic compounds intensity fell by 48 %. These results are typical cases of decoupling economic activity from resource and environmental impacts.

Cefic supported the Green Deal and Europe's ambition to become climate neutral by 2050. In May 2020, the eight-point vision for Europe in 2050 was adopted:

1. "The world has become more prosperous and more complex, with a volatile geopolitical environment that brings more economic and political integration within most regions, but more fragmentation between them.
2. Europe has developed its own different but competitive place in the global economy.
3. The European economy has gone circular, recycling all sorts of molecules into new raw materials. The issue of plastic waste in the environment has been tackled.
4. Climate change continues to transform our planet. European society is close to achieving net-zero greenhouse gas emissions while keeping all Europeans citizens and regions on board.
5. Europeans have set the protection of human health and the environment at the center of an uncompromising political agenda.
6. European industry has become more integrated and collaborative in an EU-wide network of power, fuels, steel, chemicals, and waste recycling sectors.
7. Digitalization has completely changed the way people work, communicate, innovate, produce, and consume and brought unprecedented transparency to value chains.
8. The United Nations SDGs are at the core of European business models and have opened business opportunities as market shares increase for those who provide solutions to these challenges."

Cefic has welcomed the European Commission proposal for the European Climate Law, turning the climate neutrality objective into legislation and aiming to achieve progress on the global adaptation goal. However, besides "what" the EU aims to achieve, the "how" is also important, as it will allow the EU to turn this ambition into reality. Cefic puts forward several proposals aiming to clarify, complement, or adjust certain provisions by ensuring:

- A sound and detailed definition of climate-neutrality providing a signal for long-term investments;
- A level-playing field for industry across the EU through union-wide emission reduction mechanisms (i.e., the EU Emissions Trading System, ETS);
- That all sectors of the economy contribute to the climate-neutrality objective through fair burden-sharing;
- Progress on the enabling framework for the transformation of the EU economy, in line with the trajectory for achieving climate-neutrality.

3.2. Chemicals Strategy for Sustainability

Cefic calls for a sustainability strategy that recognizes the essential role of chemicals to deliver climate ambitions and integrates multiple facets of chemicals management including safety, circularity, resource efficiency, environmental footprint, science, and innovation. The following should be the key components of the strategy:

1. Consolidating and promoting the solid foundation Europe has already built, primarily REACH regulation (Registration, Evaluation, Authorization, and Restriction of Chemicals) by its improvement, better implementation, and enforcement;

2. Adopting a proportionate and robust approach for managing to emerge, scientifically complex issues;
3. Enabling the development of truly sustainable and competitive European solutions to deliver the Green Deal.

Cefic had welcomed the EU approach to adopt the new Industrial Strategy, basing it on the European industrial ecosystems; actors agreed that the Recovery Plan should be organized around these ecosystems.

SusChem is the European Technology Platform for Sustainable Chemistry. It is a forum that brings together industry, academia, policymakers, and the civil society. An important part of SusChem is a network of national platforms (NTPs). "SusChem's mission is to initiate and inspire European chemical and biochemical innovation to respond effectively to societal challenges by providing sustainable solutions". SusChem recognizes "three overarching and interconnected challenge areas [104]:

1. Circular economy and resource efficiency—transforming Europe into a more Circular Economy. (a) Materials design for durability and/or recyclability, (b) Safe by design for chemicals and materials (accounting for circularity, (c) Advanced processes for alternative carbon feedstock valorization (waste, biomass, CO/CO_2), (d) Resource efficiency optimization of processes, (e) Advanced materials and processes for sustainable water management, (f) Advanced materials and processes for the recovery and reuse of critical raw materials and/or their sustainable replacement, (g) Industrial symbiosis, (h) Alternative business models, (i) Digital technologies to increase value chain collaboration, (j) informing the consumer and businesses on reuse and recyclability;
2. Low-carbon economy—mitigating climate change with Europe becoming carbon neutral: (a) Advanced materials for the sustainable production of renewable electricity, (b) Advanced materials and technologies for renewable energy storage, (c) Advanced materials for energy efficiency in transport and buildings, (d) Electrification of chemical processes and use of renewable energy sources, (e) Increased energy efficiency of process technologies, enabled by digital technologies, (f) Energy-efficient water treatment, (g) Industrial symbiosis via the better valorization of energy streams, (h) Alternative business models;
3. Protecting environmental and human health—safe by design for materials and chemicals (functionality approach, methodologies, data, and tools): (a) Improve the safety of operations through process design, control, and optimization, (b) Zero liquid discharge processes, (c) Zero waste discharge processes, (d) Technologies for reducing GHGs emissions, (e) Technologies for reducing industrial emissions, (f) Sustainable sourcing of raw materials, (g) Increasing transparency of products within value chains through digital technologies, (h) Alternative food technologies, (i) Novel therapeutics and personalized medicine, (j) Sustainable agriculture, forestry, and soil health-related technologies, (k) Biocompatible materials for health applications."

The new SusChem's Strategic Innovation and Research Agenda, SIRA, has five chapters:

1. "Introduction with an overview where to find the challenge areas;
2. Advanced materials: composites and cellular materials (lightweight, insulation properties), 3D printable materials, bio-based chemicals and materials, additives, biocompatible and smart materials, materials for electronics, membranes, materials for energy storage (batteries), coating materials and aerogels;
3. Advanced processes (for energy transition and circular economy): new reactor design concepts and equipment, modular production, separation process technologies, new reactor and process design utilizing non-conventional energy forms (plasma, ultrasound, microwave), electrochemical, electrocatalytic, and photo-electrocatalytic processes, power-to-heat (heat pumps, electrical heating technologies), hydrogen production with low-carbon footprint, power-to-chemicals (syngas, methanol, fuel, methane, ammonia), catalysis, industrial biotechnology, waste valorization, advanced water management;

4. Enabling digital technologies: laboratory 4.0 (digital R&D), process analytical technologies (PAT), cognitive plants (real-time process simulation, monitoring, control and optimization, advanced (big) data analytics and artificial intelligence, predictive maintenance, digital support of operators and human–process interfaces, data sharing platforms and data security, coordination and management of connected processes at different levels, and distributed-ledger technologies.
5. Horizontal topics: sustainability assessment innovation, safe by design approach for chemicals and materials, building on education and skills capacity in Europe."

3.3. Process Industry

SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) is the "European contractual public–private partnership (cPPP) involving the cement, ceramics, chemicals, engineering, minerals, non-ferrous metals, steel, and water sectors under the Horizon 2020 program. It has been successfully developing breakthrough and key enabling technologies and sharing best practices along all stages of existing value chains to enable a competitive, energy and resource-efficient process industry in Europe. SPIRE's new Vision 2050: "Towards the next generation of European Process Industries—Enhancing our cross-sectoral approach in research and innovation" foresees an integrated and digital European Process Industry, delivering new technologies and business models that address climate change and enable a fully circular society in Europe with enhanced competitiveness and impact for jobs and growth" [105]. They are contributing 6.3 million jobs in the EU. The SPIRE community has initiated 77 innovative projects with a total estimated private investment of 3 G€ (billion euros) in the last five years. Their turnover increased by an estimated 25 %—double the EU average.

SPIRE's Vision is that "the future of Europe lies in a strongly enhanced cooperation across industries—including SMEs—and across borders to become physically and digitally interconnected. Innovative "industrial ecology" business models will be developed to foster the redesign of the European industrial network. Four "technology drivers" will help the Process Industries achieve their SPIRE ambitions." Two transversal topics—industrial symbiosis and digitalization—will support and accelerate the transformations:

1. "Electrification of industrial processes as a pathway towards carbon neutrality: adaptation of industrial processes to the switch towards renewable electricity (e.g., electrochemistry, electric furnaces or kilns, plasma, or microwave technologies).
2. Energy mix and use of hydrogen as an energy carrier and feedstock: renewable electricity, low-carbon fuels, bio-based fuels, waste-derived fuels.
3. Capture and use of CO_2 from industrial exhaust gases (capture, collection, intermediate storage, pre-treatment, feeding and processing technologies, intelligent carbon management)."
4. Resource efficiency and flexibility; full re-use, recycling or recovery of waste as alternative resources: collection, sorting, transportation, pre-treatment and feeding technologies; all possible resource streams to be considered and explored (notably plastic waste, metallurgical slags, non-ferrous metals, construction and demolition waste, etc.); zero water discharge, maximal recovery of sensible heat from wastewater, the substitution of chemical solvents by water (e.g., in bio-based processes); full traceability of value chains as a crucial instrument to deploy circular business models and customers' growing demand for product-related information.
5. Industrial symbiosis technologies including industrial–urban symbiosis models.
6. Digitalization of process industries has a tremendous potential to dramatically accelerate change in resource management, process control, and in the design and the deployment of disruptive new business models.

The research and innovation efforts of Process Industries under the SPIRE 2050 Vision ultimately want to enhance and—wherever possible—enlarge the underlying value to society generated by their businesses while (a) achieving overall carbon neutrality, (b) moving toward zero-waste-to-landfill, and (c) enhancing the global competitiveness of their sectors.

4. Conclusions

The above results show that the most urgent future development areas of the process industry are climate change with GHGs emissions and ecosystems (the terrestrial one is affected by drought, wildfires, floods, glacier melting or species extinction; marine through temperature rise, ocean acidification, and sea-level rise), energy with renewable sources and efficiency, (critical) raw materials and other resources, water resources and recycling, zero waste and circular economy and resource efficiency, supply chain integration, process design and optimization, process integration and intensification, industrial ecology and life cycle thinking, industrial–urban symbiosis, product design for circularity, digitalization, sustainable transport, green jobs, health and safety, hazardous materials and waste, customer satisfaction, education, and lifelong learning.

The chemical and process industry associations (Cefic, SusChem) and their projects (SPIRE, SIRA) have added great value; therefore, they should be practiced in other continents, too. Companies and professional associations must respect international agreements and conventions (SDGs, Paris Agreement, EGD), declarations, and recommendations.

There is no doubt that existing and innovative future technologies for the efficient management of GHGs, water, energy, and raw materials will play a crucial role in transforming current chemical and bio-chemical processes into more sustainable ones. Due to their high cost, some of these technologies would need to be co-funded by governments, while others could be implemented as long-term investments at the corporate level. For example, Norway has recently announced to fund a first large-scale carbon capture and storage project "Longship" [106] (1.5 billion €). The cement and waste-to-energy plants involved in the project plan to reduce their CO_2 emissions by 50 % by capturing and storing CO_2 in an underwater reservoir in the North Sea. On the other hand, a Dutch brewery [107] has recently implemented an innovative green fuel alternative that comes in the form of metal powders [108]. Iron powder is considered as a high-density energy storage medium. It burns at high temperatures to form iron oxide, which can be reduced back to iron by electrolysis using renewable energy sources (e.g., photovoltaics) in a carbon-free cycle.

The critical step toward more sustainable processes, regardless of the novel technologies available, is the necessary shift in mindset from chasing short-term financial gains to pursuing long-term, sustainable financial, environmental, and social benefits. This step is required not only at the governance and corporate level, but also at the level of each individual.

Based on past experience, it is safe to say that advanced computational PSE tools will play an important role in the development of future chemical and biochemical processes. Today, process analysis, simulation, and synthesis/optimization tools are generally used in a sandbox mode—i.e., either in isolation from each other or in a sequential/iterative procedure. To identify truly innovative, mitigating, and perhaps even restorative solutions, these tools would need to be linked into a system that simultaneously enables detailed multi-scale modeling [109], process intensification (i.e., reduction of energy and resource requirements, waste production and equipment size, out-of-the-box process solutions/schemes) [110], and LCSA analysis.

Projects to develop sustainable processes are very demanding, both in terms of knowledge and the financial investment required to implement them. Circular economy projects often do not provide much added value. This is particularly problematic when it is cheaper to manufacture products from virgin materials than to process waste materials into secondary raw materials. The development and implementation of sustainable processes are highly interdisciplinary and involve laboratory research, pilot plant trials, process set-up, and commissioning. This is followed by the manufacturing and marketing of products and efficient waste management, which includes the reuse, recycling, and processing of waste into value-added products, fuels, secondary raw materials, or energy recovery. There is no doubt that engineers are already developing efficient computer-aided tools for developing sustainable technologies, including key enabling technologies and sustainable processes, supply chains, and networks that promote greater efficiency, waste reduction, closed loops, and eco-design. However, this will certainly not be enough to transform society from a linear to a circular economy. We believe there is still a long way to go, as changes will be needed in many areas of society, i.e., at the level of business, education, finance, politics, legislation, and society as a whole.

At the enterprise level, efforts should focus on building and optimizing value chains in which stakeholders are linked through raw material extraction, product manufacturing, transportation, collection, sorting, and processing of waste into secondary raw materials, functional materials, and energy. The aim should be to promote such industrial projects that balance economic efficiency, environmental impact, and social wellbeing. It is necessary to promote the growth of bio-based products and to seek market niches for such products.

In the field of education, young people must be encouraged to study science, technology, engineering, and mathematics (STEM), as these areas are crucial for the development of sustainable technologies and processes and the circular economy. Curricula need to be strengthened with attractive contents for young people and practical examples of green chemistry, cleaner production, eco-design, recycling, key enabling technologies, etc.

Experts in the social sciences such as psychology and sociology must also be involved in the development of sustainable processes and products, as people need to change many deep-rooted habits and understand the impact of these changes on society and the environment in order to accept them as their own. The transition from a linear to a circular society must include the reduction of inequalities in society, more equality, justice, solidarity, participation and inclusion of citizens. Art must also be involved, because products made from secondary raw materials, for example, must also be aesthetically designed if people are to accept them.

Developing sustainable technologies and implementing sustainable projects can require large financial investments, so the role of financial institutions and policymakers is also important. They must create the conditions for funding to be available for environmentally beneficial projects in the field of renewable energy, secondary raw materials, functional materials, key enabling technologies, etc. It is necessary to increase investment in education, research, innovation, and development.

The transition to a circular economy and a sustainable society can be promoted to some extent by political agreements and legal norms that impose restrictions on countries and companies in terms of emissions, proportions of recycled materials, the use of renewable resources and secondary raw materials, etc. However, in the long term, changes in existing political and wider social systems are needed, moving toward greater participation and balance, with the long-term sustainable progress of society and the protection of the environment taking precedence over the partial interests of individuals.

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