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Rethinking Energy Use for a Sustainable Chemical Industry

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The need for greater sustainability for the production of fuels and chemicals has spurred significant research to rethink the energy use in the chemical industry, and eventually substitute fossil fuel sources by renewable sources. Nowadays, the chemical industry is responsible for about one third of the total energy used - and the associated CO_2 emissions - in the industrial sector. Most of the thermal energy used in the chemical industry is not fully recovered (by process-process stream heat exchange), but removed as low grade waste heat that ends up released into the environment. Moreover, there are certain energy intensive operations such as distillation which alone is responsible for about 40 % of the energy used in the chemical process industry.
This paper aims to provide an informative perspective on the energy use in the chemical industry. The scope of this mini-review includes: current energy use, eco-efficiency aspects in chemical process industry, Process Integration for heat recovery, thermal energy upgrade by heat pumps, and advanced distillation technologies (reactive distillation, dividing-wall column, cyclic distillation) that can significantly reduce the energy usage and the carbon footprint of the modern chemical plants. Based on the provided overview, several important new research directions are defined towards rethinking the energy use for a more sustainable chemical industry.

1. Introduction

The production of energy (electricity and heat) is still largely based on fossil-fuels (coal, oil, and natural gas), and this has a strong impact on the environment. Fossil fuels do more harm than renewable energy sources by most measures (e.g. air and water pollution, damage to public health, wildlife and habitat loss, water and land use, global warming emissions). The chemical sector accounts for almost 30 % of the energy used in all industrial sectors, as shown in Figure 1 (left). To put it in context, Figure 1 shows the industrial energy sector usage (in United States), as well as the global greenhouse gas (GHG) emissions by economic sector. These figures are rather similar in other countries worldwide.

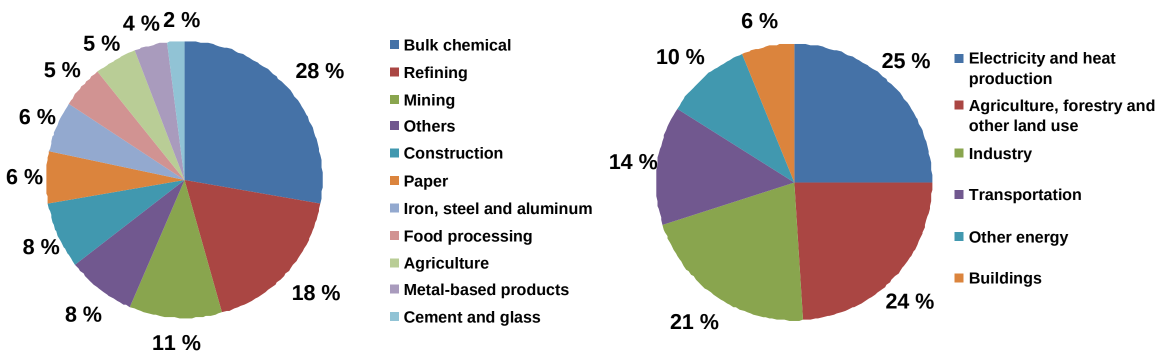

Figure 1: Left: US industrial energy sector usage in 2017 (Data source: US Energy Information Administration, Annual Energy Outlook 2018). Right: Global greenhouse gas emissions by economic sector (Data source: Intergovernmental Panel on Climate Change (IPCC), UN 2014)

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Table 1: Chemical industry overview in top EU countries (Data source: Landscape of the European Chemical Industry, CEFIC, 2018).

Country	Companies	Employees	Capital spending	R&D investment	Turnover
Germany	2,000	447,064	7.4 $\times10^9$ €	10.5 $\times10^9$ €	184.7 $\times10^9$ €
France	3,335	165,000	n/a	n/a	70.0 $\times10^9$ €
Belgium	720+	90,000	2.1 $\times10^9$ €	4.0 $\times10^9$ €	65.0 $\times10^9$ €
Spain	3,000	193,500	2.1 $\times10^9$ €	n/a	63.1 $\times10^9$ €
U.K.	3,460	140,000	4.7 $\times10^9$ €	6.3 $\times10^9$ €	59.5 $\times10^9$ €
Netherlands	470	57,000	n/a	0.75 $\times10^9$ €	55.0 $\times10^9$ €
Italy	2,800	108,100	1.6 $\times10^9$ €	0.52 $\times10^9$ €	52.0 $\times10^9$ €

Table 1 provides an overview of the key figures in the chemical industry in the top EU countries. In the European Union (EU28) the chemical sector consists of 28,329 companies (total 1,140,000 employees), with capital spending of 21.7 $\times10^9$ €, R&D investment of 9.1 $\times10^9$ €, and a turnover of 507 $\times10^9$ €. In case of the United Kingdom, the chemicals & pharmaceuticals sector is the second largest industry (after food, beverages and tobacco processing sector) with 48.7 $\times10^9$ £ revenues and 17.8 $\times10^9$ £ value added in 2016.

During the past decades, the EU chemical industry has made significant efforts to improve energy efficiency by reducing its energy use per unit of production. Remarkably, the energy intensity (energy used per unit of production) in the chemical industry (including pharma) fell by 59.7 % during 1990 - 2015. During that 25 y period, the production grew by 85 % while the fuel and power consumption reduced by 26 % (equivalent to a total of 51.8 $\times10^6$ t of oil). The 60 % reduction in energy intensity is more than the cuts achieved in the whole manufacturing industry, where the energy intensity fell by 39 % during the same period. While these achievements are commendable, there is further room for improving the energy use in the chemical industry.

This paper aims to provide a brief overview of the major energy users in the chemical industry, as well as point out new research directions aiming to rethink the energy use for a more sustainable chemical industry.

2. Problem statement

Currently, a large amount of the thermal energy used in the chemical industry is not recovered (by process-process stream heat exchange), but removed as low grade waste heat that ends up released into the environment (van de Bor et al., 2015). In addition, there are also energy intensive operations such as distillation, which covers over 40 % of the energy used in the chemical process industry (Kiss, 2013). Several methods are readily available to solve these problems – such as process integration (Smith, 2016), use of heat pumps (Kiss and Infante Ferreira, 2016), and advanced distillation technologies (Kiss, 2013) – although they have various degrees of implementation in the chemical industry. As the GHG and CO_2 emissions are largely proportional to the energy usage (when based on fossil fuels) a better way forward is needed to rethink the energy sources, distribution and use in the chemical process industry.

3. Eco-efficiency aspects

Sustainability is defined through three interconnected domains or pillars (environment, economic and social) and it is the process of maintaining change in a balanced environment, in which the resource exploitation and the orientation of technological development are all in harmony and enhance the potential to meet human needs and aspirations. When the social aspect (that is subjective and political) is not included, another term is often used frequently in industry: eco-efficiency (economic and ecologic efficiency).

According to the World Business Council for Sustainable Development (2000), eco-efficiency is attained by the delivery of competitively priced goods and services that satisfy human needs and enhance the quality of life, while progressively reducing the environmental impacts of goods and resource intensity throughout the entire life-cycle to a level that is in line with the carrying capacity of our planet. Eco-efficiency takes into account the environmental productivity and intensity of production, as well as the environmental improvement cost and cost-effectiveness. Critical aspects of eco-efficiency include: reduced material and energy intensity of goods or services; reduced dispersion of toxic materials; improved recyclability; maximum use of renewable resources; greater durability of products; and increased service intensity of goods and services.

There are several Life-Cycle Assessment (LCA)-based calculation systems on eco-efficiency, such as: BASF (Socio-)Eco-Efficiency Analysis method, and the Eco-costs Value Ratio (EVR) of the Delft University of Technology. The purpose of an eco-efficiency analysis is to harmonize economy and ecology, by carrying out an overall study of alternative solutions to include an estimation of the total cost and ecological impact over the entire life cycle. In this context, it is clear that improving the energy efficiency and saving energy play a major role in sustainable development.

4. Energy savings

4.1 Process integration

Process (Heat) Integration using Pinch Analysis is a well established methodology (Smith, 2016). The analysis of a whole chemical process leads to much more efficient solutions for saving energy (process-process heat recovery) than just by optimising the stand-alone units. Pinch Analysis can set optimum targets for energy saving, just from enthalpy-temperature profiles, well ahead the detailed design of heat exchangers (Klemeš, 2013). Pinch designates the location where the heat recovery is the most constrained, with a minimum temperature difference (ΔT_{min}) between the hot and cold streams. Targeting of energy and capital costs before HEN design (for a given ΔT_{min}) provides the minimum energy requirements (MER), utility selection and their placement, number of units and heat exchange area, as well as the cost of energy and equipment at MER. The Composite Curves visualise the flow of heat between the hot and cold process streams selected for heat integration. The Grid Diagram enables then the development of the Heat Exchanger Network (HEN). There is a trade-off between the energy savings and the capital (equipment) costs. Figure 2 illustrates the (temperature vs enthalpy) composite curves as well as the cost dependence on the minimum temperature difference (Linnhoff et al, 1979). Pinch Analysis relies on several golden rules: 1) Do not transfer heat across the Pinch, 2) Do not use cold utility above the Pinch, and 3) Do not use hot utility below the Pinch. By using process integration, energy savings of 10 – 30 % can be achieved for retrofits and new designs, in all industries not only the chemical industry. Process integration can be also applied to bio-based processes (Kiss et al., 2015).

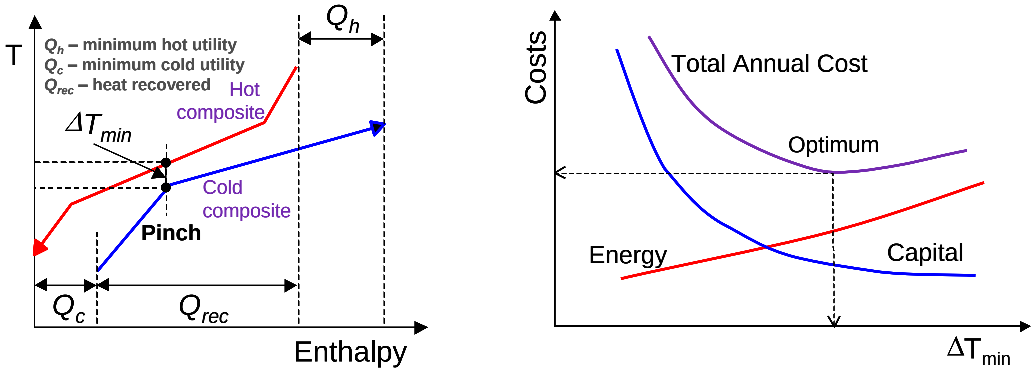

Figure 2: Pinch Analysis: Composite Curve and cost vs minimum temperature difference (Linnhoff et al, 1979)

4.2 Upgrading waste heat

The annual market potential for surplus heat from industrial processes in the UK alone amounts 36-72 PJ. Large amounts of heat contained in spent cooling water (at levels of 45 - 60 °C) are rejected to the environment. Compression Resorption Heat Pumps (CRHP) – known as hybrid heat pumps – have a high coefficient of performance (COP = 3 – 5) even at high temperature lifts (from 60 °C to 145 – 165 °C) and can provide significant energy savings (Kiss and Infante Ferreira, 2016). Figure 3 shows that a CRHP can be used to split a spent cooling water (waste heat) stream into warm and cold utility streams (van de Bor et al., 2015).

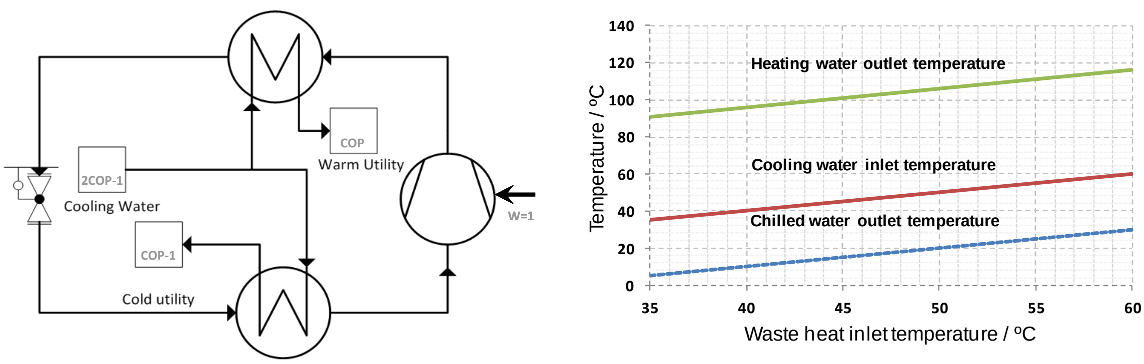

Figure 3: Splitting a spent cooling water stream into warm and cold utilities by CRHP (van de Bor et al., 2015)

4.3 Process intensification in distillation

Process Intensification (PI) is defined as a set of new innovative principles applied in process and equipment design, which can bring major benefits in terms of process and chain efficiency, lower capital and operating expenses, higher quality of products, less wastes and improved process safety. Basically, PI helps chemical engineers to achieve more (higher performance and efficiency) with less equipment and lower energy use.
Among other operations, distillation accounts for over 40 % of the energy used in the chemical industry, yet it remains the most used separation method at industrial scale (with over 40,000 columns in operation). Basically, almost every product on the market contains chemicals that went through a distillation column. However, distillation has a low thermodynamic efficiency (about 10 – 12 % in general): e.g. 5 % for C_2 and C_3 splitting, 12 % for crude separation, and 18 % for air separation (Kiss, 2013). The main problem is the use of costly high quality energy (steam) that is then rejected at low temperature (exergy loss). In the quest for improved eco-efficiency of chemical processes, higher energy efficiency and lower costs are a must win battle for the chemical industry. Among the PI technologies proposed for improving distillation, the most promising ones are in the functional (synergy) domain, as they integrate functions and steps into a single unit, thus taking advantage of synergistic effects to overcome equilibrium limitations, leading to compact equipment and increase of overall efficiency (van Gerven and Stankiewicz A., 2009). Hybrid technologies based on process intensification principles can pave the way to more efficient integrated distillation processes (Kiss and Jobson, 2018): dividing-wall column (DWC), reactive distillation (RD), catalytic cyclic distillation, and others.
Heat pump assisted distillation makes use of various heat pump concepts to upgrade the level of energy discharged and re-use it to reduce the consumption of valuable utilities. The temperature lift can be related to the temperature difference between the heat source (condenser) and heat sink (reboiler), which is determined by the product cuts that are separated. In practice, the decision to use heat pumps for distillation should follow a careful investigation of Heat Integration opportunities based on Pinch Analysis. Figure 4 illustrates heat pump assisted distillation technologies that can reduce the energy use by up to 70 % (Kiss, 2013).

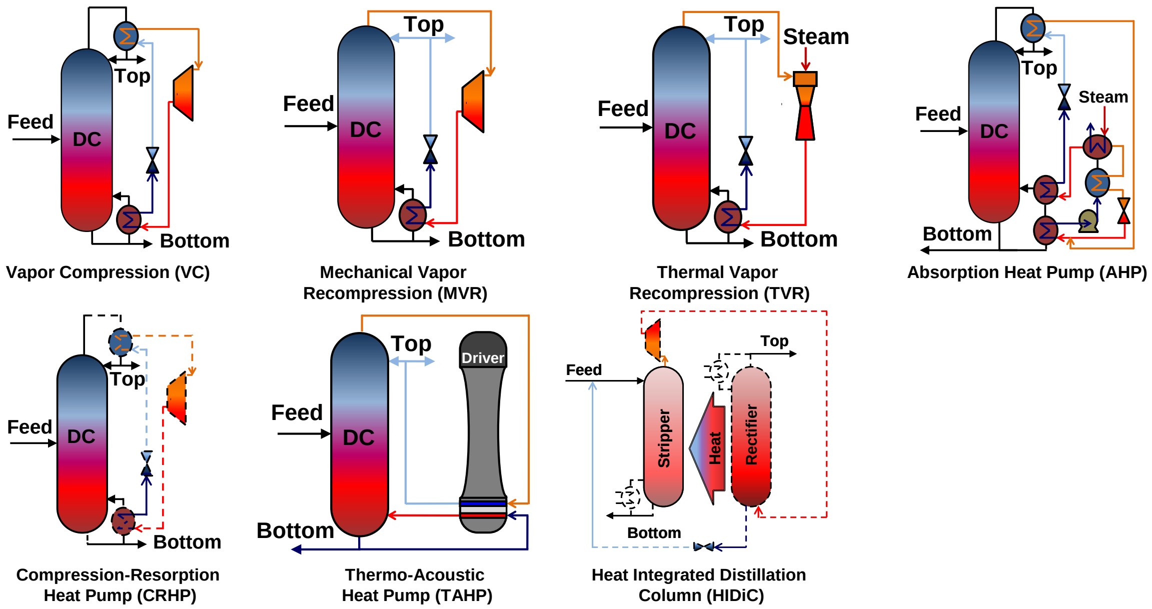

Figure 4: Heat pump assisted distillation technologies (Kiss, 2013)

Reactive distillation (RD) is a PI technique that combines reaction and distillation into a single unit, taking advantage of synergistic effects. But there must be a match between reaction and distillation parameters, as well as a difference in relative volatility of product and one reactant. In spite of a rather limited applicability range, RD allows key benefits such as: surpass equilibrium limitations, simplify complex processes, reduce investment and operating costs (usually by 40 – 60 %), less waste and fewer by-products, improved product quality, reduced thermal degradation, enhance rate and conversion, achieve high selectivity, perform difficult separations (azeotropes consumed by the chemical reaction), accomplish in-situ energy integration (heat of reaction is used to evaporate the products). Figure 5 shows the most used RD configurations (Kiss, 2013).

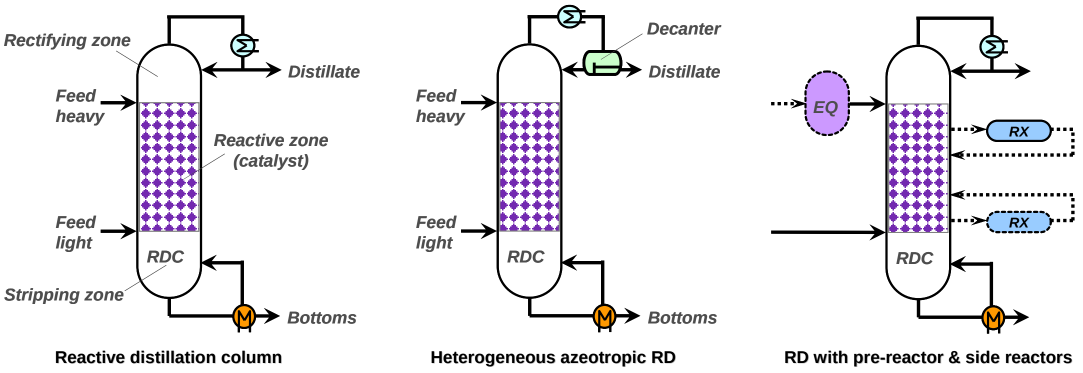

Figure 5: Reactive distillation configurations (Kiss, 2013)

Dividing-wall column (DWC) integrates two distillation columns of a Petlyuk configuration (Petlyuk et al., 1965) into a single shell. Normally, the separation of multi-component mixtures requires typically a direct or indirect sequence of at least two distillation columns. A more energetically favorable alternative configuration that avoids the remixing of internal streams is the Petlyuk configuration, in which one condenser and reboiler are effectively replaced by thermal (heat) coupling of the pre-fractionator with the main column, while the required condenser and reboiler are attached to the main column. DWC is basically a practical implementation that allows further equipment integration and cost savings. Figure 6 illustrates the typical DWC configurations used for ternary separations, as well as reactive / azeotropic / extractive distillation (Yildirim et al., 2011). DWC technology offer key advantages such as: improved thermodynamic efficiency, high purity also for the middle product stream, compact configuration (2 columns in 1 shell), around 25 – 30 % energy savings (due to no remixing effect), lower capital investment by 20 – 30 % (due to using only 1 reboiler and 1 condenser). It is effectively applicable to many processes, with a large range of applications. As drawbacks, DWC allows one operating pressure, it has a higher pressure drop and temperature span along the column. The main industrial players include: BASF, Julius Montz, Linde, Uhde, Lonza, UOP, GTC Technology, Sulzer, Koch-Glitsch.

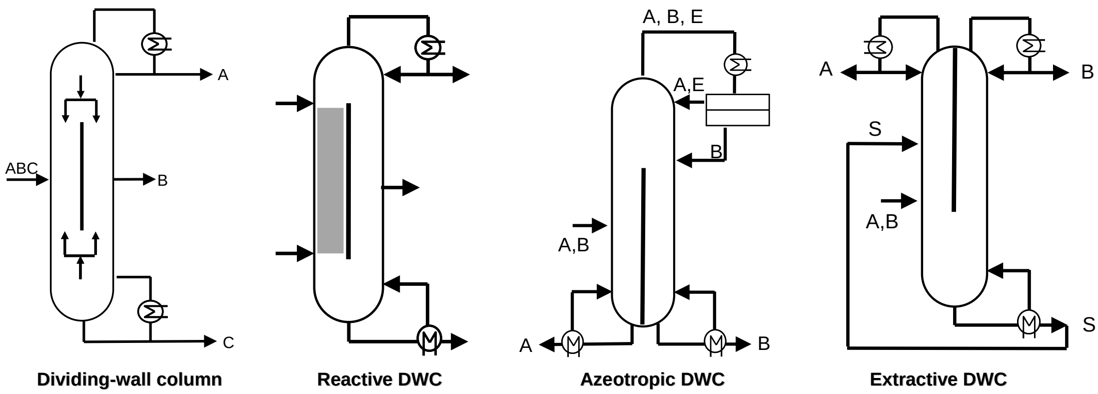

Figure 6: Dividing-wall column configurations for various operations (Yildirim et al., 2011)

5. Rethinking the energy use

Chemical processes are basically clusters of sources and sinks of material and energy, connected through various streams. The aim here is to identify and connect these sources and sinks in a smart way, in order to minimize the demand for costly material streams and utilities, as well as the output of (hazardous) emissions and non-product chemicals, while developing substantially smaller, cleaner, safer and more energy efficient and sustainable technologies. In this respect, the following main future research directions are envisaged:

- Flexible supply and demand technologies. The availability of cheap renewable energy (e.g. solar, wind) is dramatically changing the energy sector and the landscape of power plants. However, the day-to-night and seasonal variability of renewable energy sources also creates tremendous challenges for power plants as well as chemical processes. Nonetheless, these can be turned into opportunities by matching the dynamics of the power plants with flexible demand technology in the chemical process industry – that is to use the excess of electricity when available instead of storing it in a rather expensive way.

- Smart chemical clusters and energy hubs. The design and optimization of integrated chemical clusters should be done (using a decision-support framework) by identifying the most viable feedstock, energy sources and production pathways, taking into account sustainability metrics. Also, distributed networks of energy hubs should be developed to achieve higher industrial energy efficiency (30 – 50 %). A framework must be capable of design and optimisation of such hubs, considering specific (local/regional) industrial energy needs such that it will serve as a powerful tool for reducing energy use and GHG emissions alike.
- Eco-efficient biorefineries. Although most research in biorefineries focuses on conversion or pre-treatment steps, the largest costs are in the downstream processing of bio-based chemicals and biofuels. In order to become viable and sustainable, a paradigm shift is needed towards intensified separations. Separations must be integrated and intensified as part of a systematic and holistic approach, as changes to the way separation is carried out cannot be studied in a piecemeal approach by considering units in isolation. This direction should aim to integrate various separation techniques for optimal process design, using novel technologies and configurations developed specifically to suit difficult bio-separations involving complex mixtures where the useful products are in low concentration. This can be achieved by exploiting the synergy between the physical and chemical phenomena taking place in multi-phase systems where the products are obtained by bio-chemical reactions or isolated from natural resources.
- E-refinery platform. The abundance of cheap renewable energy (solar, wind, hydro- and geothermal) stimulates the electrification of chemical industry and reshapes the landscape of utilities. The e-refinery concept (promoted by TU Delft) is based on using biomass, water, air (CO_2, O_2, N_2) and renewable electricity for the large-scale electrochemical production of simple molecules. A collective effort from a wide range of disciplines is required to realize the large scale implementation of e-refinery. Process systems engineering (PSE) will play a key role here, by providing a holistic view of the involved processes phenomena, micro and macro processes, process design and experimental validation using pilot plants.

6. Conclusions

Rethinking the energy use in the chemical process industry is imperative for improving the sustainability of the chemical sector. Several concluding remarks can be drawn based on the overview provided in this study:

- Combining Process Integration (heat recovery and upgrading) with PSE and PI techniques is strongly required for the development of more sustainable chemical processes (i.e. over 50 % pollution reduction).
- Hybrid separation technologies based on process intensification can pave the way to more eco-efficient processes (less equipment required and energy savings around 50 %), especially needed in biorefineries.
- Novel processes must be designed such that they take maximum advantage of harvesting the renewable energy sources, use energy in a flexible way, and move away from thermal to electrochemical conversion.

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