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Energy and CO_2 management for chemical and related industries: issues, opportunities and challenges

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Abstract

This paper gives a brief review of energy and CO_2 emissions related topics resulting from the chemical and related industries. The main issues, challenges and opportunities are highlighted together with perspectives of process alternatives for more efficient energy consumption and CO_2 emission management. Analysis of the data indicate that not all available energy resources are being utilized efficiently, while the energy resources causing the largest emissions of CO_2 are being used in the largest amounts. Also, the chemical and related industries are among the largest consumers of energy, indicating that solutions for reduction of energy consumption and CO_2 emissions in these industries need to be investigated. Information on promising alternatives for reduction of energy consumption and CO_2 emissions are collected and a selection of them are evaluated. Also, two specific case studies involving energy intensive separation operations replaced by recently developed technologies that may achieve significant reductions in energy consumption, CO_2 emissions and total annualized costs are presented. Through these examples issues of energy need versus CO_2 neutral design, sustainable conversion, retrofit design, and process intensification for chemical and related industries are highlighted.

Keywords: Energy resources, Energy consumption, CO_2 emission and management, Sustainable process alternatives

Background

The human race is the master of the planet earth because it has managed to convert the available resources to desired products (fuels, cars, planes, polymers, drugs, food, cloths, etc.) that it needs for survival and sustainability. The chemical and related industries continue to play an important role in this respect. However, the processes employed to convert the resources to the desired products use energy, cause negative environmental impacts and also produce waste. The rate of utilization (consumption) of energy in different forms has been increasing continuously at a rapid pace, especially in sectors such as transportation, industrial and residential since the 1900s. Energy consumption per capita is an important parameter to assess the quality of life for the population of a country. Therefore sustainable harnessing of the available energy resources with a view to meeting the necessities of increasing world population, to ensure safety and health of the present as well as the future generations on earth, should be an essential goal of all governmental planning [1]. With the rapid industrialization and growth in population, the demand for energy is increasing continuously. However, because of the cost and availability, the most used sources of energy are non-renewable, which also has the largest effect on the environment because of the emission of CO_2 other green-house gases.

Energy is needed in some form, directly or indirectly, for almost all of our activities within sectors such as transportation, commercial, industrial and residential. The energy needs (demands) for different sectors are met through different sources of energy that are dependent on geographical location, availability, cost of harnessing as well as environmental effects. Availability of the energy resources is not uniform across earth and neither are costs or needs. The sources of energy can be broadly classified as conventional and unconventional. Conventional sources of energy are the natural fossil

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energy (coal, oil, natural gas, etc.) and nuclear energy resources, which are generally accepted as fuel resources to produce heat, light, food and electricity. Unconventional energy resources are classified as solar, wind, biological wastes, hot springs, tides, biomass, etc., that may also be used to generate heat and power. Unlike the conventional fossil energy resources, which are non-renewable, limited in terms of availability and cause pollution (for example, emits CO_2 to the atmosphere), the unconventional energy resources are renewable, are present in abundance in nature and they generate much less pollution throughout their lifecycles. Their utilization is however limited by the available technologies to convert them to usable energy forms.

Initiatives to capture the released CO_2 is therefore similar to trying to *cure* the pollution problem after the incident has occurred. However, as the amounts and sources of energy used effect earth's environment and thereby it's sustainability, to meet energy demands, the conventional resources need to be supplemented with the unconventional resources so as to manage the CO_2 and other GHG emissions at acceptable levels, and thereby *prevent* the pollution problem.

Recently, Vooradi, et al. [2] provided a detailed overview of the different types of energy resources versus their current levels of consumption, while Gani et al [3] highlighted some perspectives on how to manage the process energy demands versus CO2 emissions in a short conference proceedings paper Using these developments as the basis, this paper further extends the discussion with additional data on industrial energy utilization versus CO_2 emission and, analysis related to new developments in the area of synthesis-design of more sustainable chemical and related processes. In particular, use of techniques such as process intensification, process integration and energy integration at different levels, that aims to minimize the energy consumption (demand) and *prevent* the pollution problem rather than *cure* it after the incident has occurred, are highlighted. That is, *prevent* the pollution problem through more sustainable process alternatives. Therefore, the objective of this paper is to review the current status in terms of issues (energy consumption by the chemical and related industries; the associated CO_2 emissions; and the need for their reduction), opportunities (means available to simultaneously increase process efficiency and reduce CO_2 emissions) and challenges (how to achieve the targeted process improvements including economic feasibility also). Different options for process improvements proposed by others are also evaluated.

The current energy status with respect to resources and their consumptions is briefly reviewed, followed by a brief discussion on the issues, challenges and opportunities for reduction of energy consumption, CO_2 emission as well as economic feasibility. Alternatives for achieving targeted process improvements are then evaluated and details of two specific case studies applying recently developed energy reduction technologies are highlighted. The paper ends with future perspectives and conclusions.

Review of Energy status

Figure 1 shows the energy consumption in different sectors in 2015 and 2016 [4] and it is clear that the industry and transportation sectors are more energy intensive than others. The industrial sector alone is responsible for 37% of the total energy consumption and 24% of the total global CO_2 emissions [5]. The global CO_2 emissions from fossil fuel usage is around 31.4 billion tons per year. To limit the scope of this paper, only the energy and CO_2 management issues for the chemical and related industries are considered.

Energy consumption in the industrial sector

Analysis of the data show that USA, European Union, China and India consume nearly 60% of the total global industrial energy consumed. During 2010–2016, the highest annual growth rates in industrial energy consumption are found in the Middle East (2.5%), China (2.6%), South Korea (2.7%) and India (4.7%) [6]. In the industrial sector, according to the International Energy Outlook (IEO) [7], the five main sources of energy are liquid fuels, natural gas, coal, electricity (generated through various energy resources) and renewables. According to IEO [8], in 2014 the distribution of energy resources for electricity generation is the following: coal at 40.8%, natural gas at 21.6%, nuclear at 10.6%, hydro at 16.4%, other sources (solar, wind, geothermal, biomass, etc.) at 6.3% and oil at 4.3%. Increasing use of unconventional sources of energy for electricity generation is a welcome trend.

Most industrial energy consumption occurs in the manufacture of bulk chemicals and petrochemicals, iron and steel, nonmetallic minerals, and nonferrous metals. The chemical and petrochemical industries are among the largest energy consumers with 1078 Mtoe of energy consumption in the year 2016. Between 2000 to 2016, these industries had a 2% annual rate of increase in energy consumption versus a 2.5% annual rate of increase in CO_2 emission. In USA, the bulk chemical industry is still the largest industrial consumer of energy, followed by the refining industry and the mining industry, which account for 28, 18 and 11%, respectively, of the total USA industrial sector energy consumption [7]. Other related energy intensive processes are the iron and steel industry (with a global energy demand of 819.23 Mtoe in 2016) and the cement industry (with a global energy demand of 250.7

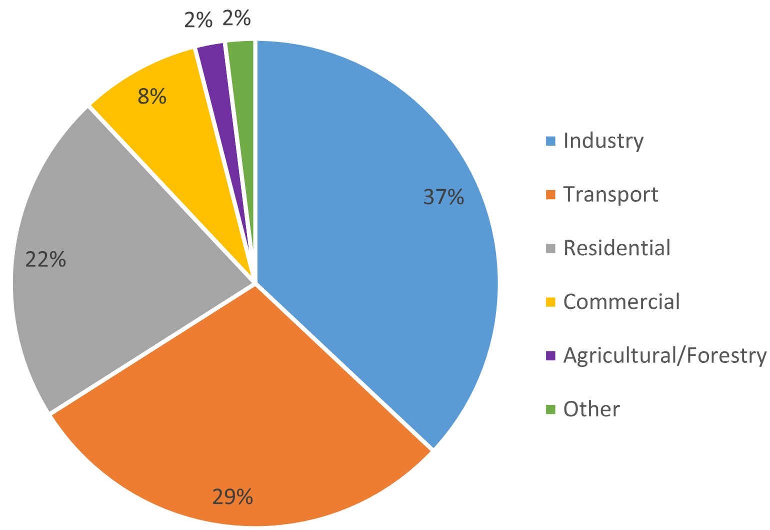

Fig. 1 Percentage of total energy consumption by sector in 2015 and 2016

Mtoe in 2016). Clearly, reductions in the energy consumptions in these industries can help to bring down of the global CO_2 emission rate.

Energy supply for the industrial sector

How is the energy needed by the industrial sector, especially the chemical and related industries, supplied? From an energy consumption point of view, the chemical and related industries could be considered energy *demanding* technologies that need to be serviced by energy *producing* technologies, which supply the demand in various forms. Selection of an energy resource to meet any demand is based on the following factors: resource availability, geographical location, harnessing technology, associated costs and environmental effects. Conventional resources such as coal, oil, natural gas and wood, which all contribute to CO_2 emission, are still the primary resources for energy generation globally. Other resources of energy that do not release CO_2 are solar, wind, geothermal, nuclear, and biomass. Figure 2 shows recent energy consumption statistics in the industrial sector and the projection as per Sustainable Development Scenario (SDS) targets of the International Energy Agency (IEA) [9] for different fuels. Clearly, despite the projected growth in industrial production needed to sustain the demands of an increasing global population, the growth in energy consumption by industry needs to be restricted to 0.9% per year to realize the SDS objectives by 2030. In April 2018, the average concentration of atmospheric carbon dioxide is above 410 ppm measured at Mauna Loa Observatory in Hawaii [10] and it has been the highest monthly average in history.

To arrest the increase of greenhouse gas concentrations in the atmosphere, IEA proposed a plan for reduction of CO_2 emission through different means as shown in Fig. 3. An important issue to note in Fig. 3 is that energy efficiency plays a major role, which also affects the process sustainability in terms of reduced operating cost, reduced environmental impact and reduced waste [2]. Therefore, research needs to be focused on technologies that can provide energy efficiency improvements through sustainable process engineering and the adoption of energy management systems and practices with the goal of energy demand reduction as well as meeting these demands with more sustainable energy supply. To meet the energy demand utilization of a single energy resource may not be a viable or sustainable option. Hence, sustainable integration of geographical (local) industrial energy demands with energy supply capacities (i.e., energy from solar, wind, geothermal, biomass, fossil fuel with CO_2 capture, etc.) can result in better utilization of energy resources, leading to a better environment.

Issues, challenges and opportunities

With the rapid industrialization and growth in population, the demand for energy is increasing continuously. However, because of the cost and availability, the most used resources of energy remain non-renewable, which also have the largest effect on the environment because of the resulting emissions of CO_2. Among the challenges that are currently being considered, one of the most important concerns is energy as it effects directly and/or indirectly most of the other challenges related to water, food and environment. The issues discussed in this paper are how the energy demand is supplied, which resources could be used, and what are the associated

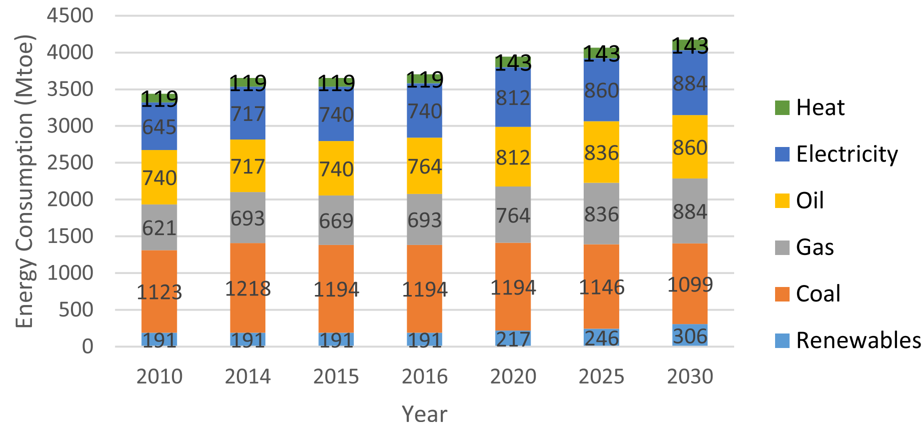

Fig. 2 Fuel wise energy consumption in the Industrial sector [9]

environmental impacts with respect to the chemical and related industries.

Energy resources

The main issue is the availability of the energy resources, which is not uniform across earth, neither are costs or needs. The conventional resources of energy are naturally available but there are extraction costs, which is related to the location of the energy resources (underground, or deep underground or under the sea bed, for example). The technologies to extract these resources are, however, more developed than the unconventional energy resources. The latter, generate much less pollution throughout their life-cycles but currently their conversion to usable energy forms is more expensive than the conventional resources. Therefore, they are under-utilized for industrial needs. Table 1 gives a list of known resources of energy along with their levels of utilizations (adopted and extended from Vooradi et al. [2]) as well as perspectives/remarks related to their utilization. With the various sources of energy available, the challenge is to reduce the utilization of fossil-based resources and to increase the non-fossil-based sources, capture and sequestrate or utilize the captured CO_2, and reduce the energy demand.

Energy consumption: Conversion of resource to energy form

The main issues, challenges and opportunities are all related to converting the available energy resources to the required form while simultaneously reducing the resulting CO_2 emission. As pointed out by Gani et al. [3], depending on the specific application, the available resources of energy are converted into potential energy (any type of stored energy, for example, chemical, nuclear, gravitational, or mechanical) and/or kinetic energy, which is related to movement (for example, electricity is the kinetic energy of flowing electrons between atoms which does not release CO_2). Note that the kinetic energy that helps the wheels to rotate in an automobile is the transformed potential energy trapped in gasoline,

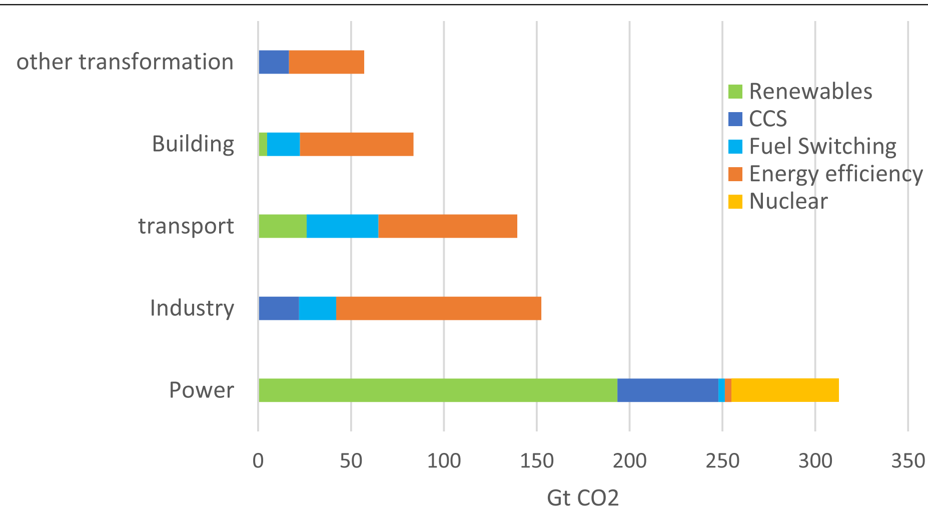

Fig. 3 CO_2 emission reduction targets and the means to achieve them [73]

Table 1 Availability of energy resources and utilization [78]

Energy	Availability/ Installed capacity	Utilization	Global energy consumption	Required electricity	Perspectives-Remarks
Fossil fuels					
Oil	1656 Bb	34.24Bb/year	32.9%	4.1%	?
Coal	891.53 Bt	7.80 Bt/year	30%	39.3%	Decreasing production
Natural gas	1.87 × 105 Bcm	3538.60 Bcm/year	24%	22.9%	Increasing production All these sources release CO2
Nuclear	382.90 GW	2.44×10^6 GWh		11%	Safety & hazards issue need to be resolved; potential to supply increased amounts of energy
Hydro power	1212.30 GW	3.97×10^6 GWh		16.4%	Increasing growth in installed capacity
Solar energy	227.10 GW	2.53 × 105 GWh		1%	Scope for improvement; current technology economically not feasible or sustainable
Wind power	431.95 GW	8.4×10^5 GWh	7%	4%	Scope for improvement; high cost technology
Bio-based	??	??	??	??	Availability of substantial sources, ensuring national energy security, enhancing rural employment and agricultural economy, low CO2 emissions. Issues of food versus energy, deforestation, availability of land, etc., need to be resolved.

Units: Bb-Billion barrels, Bt-Billion Tons, Bcm- Billion cubic meter, GW- Giga Watt

and results in CO_2 emission. Another common example of transformation of energy from one form to another is in a power plant. However, power plants using non-renewable energy resources (coal, natural gas, oil, wood) transform the chemical potential energy trapped in the fossil fuels to electricity (releasing, thereby, CO_2); while nuclear power plants change the nuclear potential energy of uranium or plutonium into electricity, wind turbines change the kinetic energy of air molecules in wind into electricity, hydroelectric power plants transform the gravitational potential energy of water as it falls from the top of a dam to the bottom into electricity and biomass is converted to different types of fuels by, for example, combustion, pyrolysis or chemical conversion. Although different alternatives are available to generate the kinetic energy, currently fossil fuels are mainly used to meet the current global energy demand.

Figure 4 shows the CO_2 emission statistics of the four largest emitters compared to the rest of the world with respect to fuel combustion from 2015 to 2017 and the percentage change in the corresponding emissions. The data reported in Fig. 4 (a) highlights the continuous increase in global carbon dioxide emissions from 2015 to 2017. In the year 2017, the CO_2 emissions were 680 million metric tons higher than in 2016. The percentage increase in global CO_2 emission from 2016 to 2017 is 2.12, whereas only 0.8% increase is reported for the year 2016 as compared to the previous year. The CO_2 emissions from the European Union increased by 1.9% in 2017 as compared to 2016, despite the negative trend in overall energy production. As highlighted in Fig. 4 (b), India and China are showing lower CO_2 emission rates in recent years, compared to the average emissions over the last seventeen years.

Figure 5 shows the total energy consumption from different fuel sources. From Figs. 5 (a), (b) and (c) it can be observed that fossil fuels are the most used. Oil and natural gas consumption are increasing steadily even after

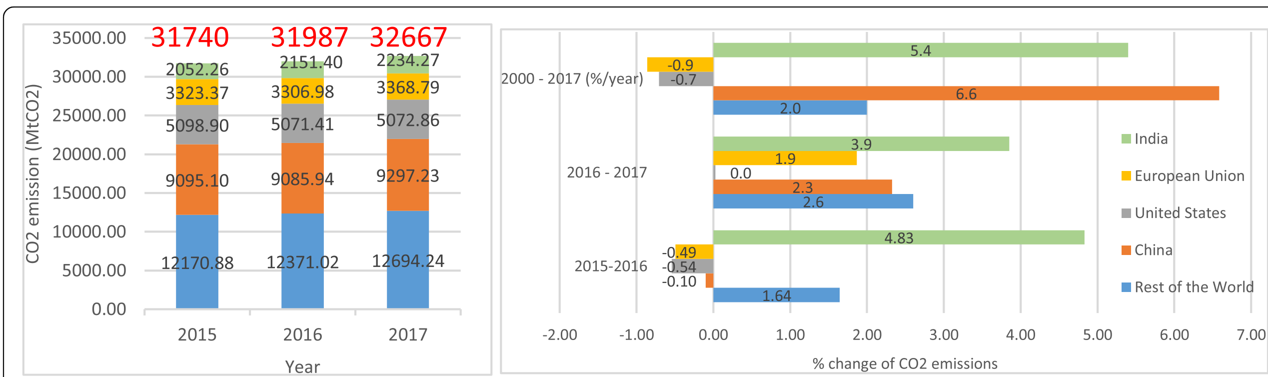

Fig. 4 Country wise statistics (**a**) CO_2 emission due to fuel combustion during 2015–2017 (**b**) Percentage change in emission [74, 75]

Fig. 5 Energy consumption from different fuel sources (**a**) Oil; (**b**) Natural Gas; (**c**) Coal; (**d**) Nuclear; (**e**) Renewable [76]

the Paris agreement [9]. The world coal consumption, however, has remained constant in the last three years. China consumes more than 50% of the total world coal consumption (see Fig. 5 (c)). Figure 5 (d) shows the world energy consumption from nuclear fuel. The rate of increase in the utilization of nuclear energy is not very high and at present only nuclear fission is used for energy generation. Though this technology has the advantage of lower CO_2 emissions, the challenges in terms of management of radioactive wastes, non-ecofriendly production of nuclear fuel and likely radiation released from accidents are important concerns that need to be addressed. The energy consumption from renewables is showing the highest rate of increase, compared with energy consumption from the other sources. Figure 5 (e) shows the world renewable energy consumption for the last three years. Note, however, compared to the energy consumption from other resources, the total renewable energy consumption is quite low.

Options such as fuel substitution (change the fuel used to provide energy to the chemical process and include options such as biomass fuel and/or use low-carbon methane) and Combined Heat and Power (CHP) generators (reduce emissions by using CHP generators to provide energy and thereby, reducing emissions from the fuel used) are alternatives worth considering.

Energy consumption: Utilization in manufacturing processes

Here, the main issues, challenges and opportunities are related to how to design and operate manufacturing processes so that the SDS target can be satisfied? This means that the current practice of predominant use of fossil fuels as the energy resource must not continue and there is an urgent need to reduce the CO_2 emission and thereby, global warming through a better management of energy supply and consumption together with the associated CO_2-emissions. Note that the chemical and related industries are highly energy intensive, often operating at high temperatures and consequently requiring high energy inputs. Many different process technologies are used by these industries, ranging from large-scale continuous processes making high volume bulk products, to small batch processes making specialty chemicals and intermediates. Many of the intermediate products are further converted by other industries to chemical-based products (such as cosmetics, soaps, detergents, etc.) while the bulk chemicals are used in a wide variety of industrial manufacturing processes involving plastics in primary form, paints, rubber, fertilizers and pharmaceuticals. The automobile, aerospace, construction, food and drink, and energy sectors are all major users of chemical products. The challenges and opportunities are related to the simultaneous reduction of operating costs, energy utilization, global carbon dioxide emissions, as well as safe and better operability of the process. The following options should be considered [2, 11]:

- improvement of process efficiencies to reduce energy consumption, including energy integration, mass integration, efficient separation, etc.;
- feedstock switch/substitution as well as new processing pathways;
- new process technologies, such as process intensification;
- clustering such as sharing of utilities (energy, water) and raw materials to increase efficiency and reduce overall emissions;
- application of carbon dioxide capture, sequestration and utilization (CCS and U) technologies.

For a more sustainable energy management scenario, not just one of the above approaches, but a judicious mix of all should be employed. Also, any new approach to CO_2 emission reduction would need to address issues of economic feasibility, energy consumption and related direct-indirect CO_2 emissions together with other performance factors. Therefore, the availability of energy resources, the CO_2-emission and management and sustainability of manufacturing process alternatives need to be carefully studied to determine the best options. Some of the technologies that may be used to reduce energy demand by more efficient use of energy within the process and thereby reduce the CO_2 emission are considered below in section 3. The overall objective is to reduce energy consumption, which will reduce operating costs (in processes where the energy costs are dominant) and thereby reduce CO_2 emission. That is, reach a zero or negative CO_2 emission, if economically feasible.

Energy efficient technologies

According to Dukes [11], a number of opportunities exist to achieve more sustainable process alternatives. The alternatives are broadly classified and presented in Table 2. Not all the mentioned alternatives in Table 2 are applicable in all chemical and related processes. The goal should be to identify which of the above alternatives are promising and to check whether they meet the desired targets for improvement. Applications of a collection of these technologies are highlighted below.

New technologies

The chemical industry is known for converting resources such as petroleum, biomass, natural gas, rock, salt, etc., to a set of basic commodity chemicals such as ammonia, benzene, ethylene, propylene, sulfuric acid, etc. The technologies used to produce these basic chemicals are continuously being improved with a view to minimization of energy consumption, carbon footprint (a measure of CO_2 emission) and costs. As the population on earth is increasing, the need for these basic chemicals is also increasing, which in turn, require more energy and water, and thereby cause more negative environmental impact, unless new technologies are introduced. Technological developments related to production of two chemicals, ammonia and benzene are briefly reviewed below.

Table 2 List of opportunities for more sustainable process alternatives

Sustainable Fuel	Sustainable Chemicals	Energy efficiency	Other Options
Biomass as fuel; Waste as fuel; Decarbonised methane as fuel; Low carbon electricity; Hydrogen by electrolysis – Ammonia; Hydrogen by electrolysis – Hydrogen; CCS - combustion (incl. biomass); High temperature steam electrolysis;	Biomass as feedstock; Recycled plastics – syngas; Retrofit oxygen-depolarized cathodes (ODC) for chlorine production; Methanol-to-olefins; CCU, High temperature cracking; Catalytic cracking; Bioprocessing;	Process Intensification, Improved waste heat recovery; More efficient equipment; Improved steam system efficiency; Combined heat and power (CHP); Integrate gas turbines with cracking furnace	Improved process control; Membrane technology; Process Intensification, Solid state synthesis; Clustering; Improved insulation;

Ammonia production

Ammonia is one of the most important chemicals and the feedstock for major synthetic fertilizers. In conventional ammonia synthesis processes, the required hydrogen can be produced from fossil fuels by steam reforming [12] and partial oxidation [13]. Use of fossil fuels make these processes highly carbon intensive. Retrofitting of existing conventional processes characterized by preheating of combustion air [14], hydrogen recovery from the purge gas [14, 15], improved CO_2 removal systems [16], indirect cooling of the ammonia synthesis reactor [17] and use of smaller catalyst particles in ammonia converters [18] have resulted in significant reductions in energy consumption and CO_2 emissions. Also, although hydrogen produced from water electrolysis using renewable or nuclear energy offers a promising sustainable option in terms of CO_2 mitigation, it is still associated with major challenges such as immature technology and high costs [19, 20]. An integrated approach to combine power generation and ammonia production, offers promising alternatives.

Benzene production

Aromatics are generally ring structured chemicals such as benzene, toluene, and xylene. These chemicals are mainly used as solvents and as feedstock for the production of polymers and various consumer products such as pharmaceuticals, paints and polishes. Benzene is one of the highly used aromatics, even though it is carcinogenic and therefore must be handled very carefully. The world benzene production is expected to increase by 10% within 2020 [21] from 44.5 Million mt in 2014 [21]. China, USA and Western Europe together consume more than 60% of the global production of benzene [22]. Benzene is produced from hydrocarbons by energy intensive catalytic conversion techniques. At present, different experimental studies are exploring the development of efficient catalysts for high feed conversion and yield of benzene: Upare, et al. [23] reported cobalt promoted Mo/β zeolite catalyst using a co-impregnation method and studied the effect of cobalt loading on catalytic activity. Perez-Uresti, et al. [24] worked on energy saving, economic analysis and environmental assessment in terms of CO_2 emission for the production of benzene from shale gas via direct methane aromatization (DMA). This technology results in a high return of investment. Production of aromatics from methanol, which may be produced using captured CO_2 could be a more sustainable option as it will reduce the use of fossil fuels as a feedstock in conventional naphtha steam crackers [5]. As in ammonia production, an integrated approach to combine power generation and benzene (and other related chemicals) production, offers promising alternatives.

Integration of energy demand and supply

Two technologies are considered here – technology that supplies the required energy form; and, technology that uses (that is, energy demand) the supplied energy to convert feedstocks to useful products. The objective here is to integrate these two technologies to match the targets for improvement, that is, more sustainable production. The above integration can be achieved at various levels: unit operations, processes, industry and region (industrial area, city, state or country), which are discussed below.

Integration at unit operations level

Energy integration at the unit operation level has been very well studied by many researchers and some of the popular techniques for effective thermal integration are based on: thermal pinch techniques [25], temperature interval diagram [26] and grand composite curve (GCC) [27]. The requirement of fresh utility can be minimized by exchanging energy between the units/streams. For instance, a hot stream, which requires cooling is integrated with a cold stream, which requires heating; or, an exothermic reactor is integrated with energy demand units such as a heater. A specific minimum utility target (amount of fresh steam needed as energy) is determined in terms of how much fresh utility can be saved by integrating the unit operations that need the utility with the unit operations that supply the needed utility.

Energy integration at process/site level

Energy integration at process level includes combined heat and power integration where heat pumps, heat engines and cogeneration are considered. Different integration approaches are considered with the goal to optimize the overall process utility targets such as, i) cogeneration targeting: methods based on exergy and energy analysis [28], turbine hardware models [29], integration of steam driven chillers into site utility system [30]; ii) Combined cooling, heat and power (CCHP) systems: different mixed integer linear programming (MILP) and mixed integer non-linear programming (MINLP) models to optimize the cooling, heating and power requirement for the process/site [31, 32]. Reducing the utility targets without accounting for the core process may not result in an optimal solution, as the energy demand within the process can also change due to changes in the condition of operation. Hence, overall process material and utility integration as shown in Fig. 6 can give globally optimal solutions compared to without this integration.

Energy integration at region level

Energy integration at region level mainly involves resource re-allocation. Currently, most of the region's energy demand by the end user is being met by the cheapest available

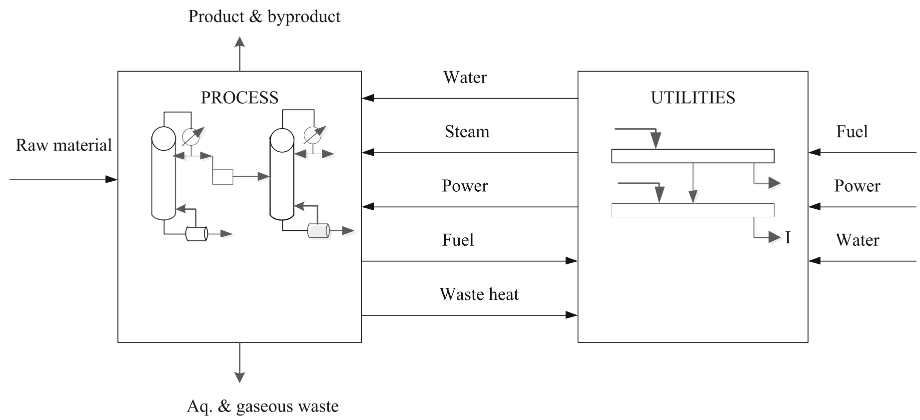

Fig. 6 Interaction between core process and utilities (Adopted from Mahmud, et al [77])

sources and there is no discrimination based on the grade or quality of the energy in use. For example, in tropical regions use of solar or thermal energy can be a sustainable option for domestic water heating. However, with the currently available technology, its maturity and costs, electricity (high grade energy) is still widely used for domestic water heating. Superstructure based optimization techniques successfully applied in process synthesis can be adopted to find appropriate energy resources matching with energy demands [3], which can be evaluated through a life cycle assessment of available energy resources and energy production technologies under consideration. This can ensure that an appropriate choice of the energy resource together with its production technology is matched with the existing energy demand of the desired quality. Sustainable solutions to address the environmental problems (for instance, CO_2 emission) at process scale can be obtained through this integration.

Integration for CO_2 neutral process design

As pointed out by Gani et al. [3], this option is not really *preventing* the pollution problem but it nevertheless promises the potential to significantly reduce the CO_2 emission as well as points to issues that need to be resolved if the energy consumption versus CO_2 emission management should find more sustainable solutions. Roh, et al. [33] and more recently Bertran, et al. [34] have shown that the CO_2 released from power plants can be captured with currently available technologies and converted to chemicals such as methanol, dimethyl ether, dimethyl carbonate, succinic acid and many more with a net CO_2 emission of zero or negative (CO_2 released minus CO_2 utilized). The problem, however, is that the demands for the chemicals produced are currently so low that the CO_2 captured from only a few power plants of standard size is enough to cover these demands. Note that this is a pollution *curing* problem after it has occurred, making the problem more difficult to solve. To make a significant impact, the demands for the considered chemicals need to increase or the power plants need to switch from fossil to unconventional resources, thereby, *preventing* the pollution problem.

Process re-design for reduction of energy demand

The main energy source in both organic and inorganic chemical processes is steam followed by potentially recovered energy. Furthermore, about 50% of the energy consumed in chemical processes is used for purifying products and byproducts or within recycle streams. This indicates that there are large opportunities for reducing the process energy consumptions in chemical and related processes. Therefore, research in this industrial sector has a high potential for success with respect to reduction of energy demand by improving the energy efficiency of individual process units and/or plants. Process systems engineering (PSE) has evolved into an important field of chemical engineering by providing systematic methods and tools for sustainable design of chemical plants. In this respect, process intensification and process integration play significant roles by providing means to increase energy efficiency and mitigate CO_2 emissions from chemical and petrochemical industries. In this section, the scope and significance of process intensification and integration are highlighted. The first involves the application of a new recently developed technology and the second highlights the perspectives of a promising technology.

Hybrid separation: New application example

Separation operations are needed in almost all chemical and petrochemical industries and they affect not only production issues related to the product, but also the associated energy consumption. According to Sholl and Lively [35], chemical separations alone account for 45–55% of the industrial energy use in USA, and for 10–15% of the nation's total energy consumption (commercial, transportation, residential, and industrial uses combined). Distillation and other thermal separation methods (such as drying and evaporation) account for 80% of the energy consumed for industrial separations, and therefore constitute the most attractive target for improvement.

Distillation is still the primary choice to carry out the separations because of its inherent advantages such as established technology, high purity of products and high throughput, despite its low thermodynamic efficiency and high energy intensity. Several process intensification techniques have been investigated: dividing-wall columns [36], heat-integrated distillation column [37], heat pump distillation [38], multi-effect distillation [39], membrane distillation [40], and hybrid schemes with membrane modules [41]. In the hybrid scheme, to increase the energy efficiency of a required separation task (for example, replace the operation of a single distillation column with that of a hybrid scheme, where the same distillation column is operated integrated to a membrane unit operation) that satisfy the required separation specification while requiring significantly smaller amounts of energy.

Vooradi, et al [2] investigated the viability of hybrid schemes i.e., distillation coupled with a membrane operation for separation of a binary azeotropic feed mixture of benzene (750 kmol/h) and cyclohexane (250 kmol/h) to the target purity of 99.5% for both components. The mixture forms a pressure insensitive azeotrope and at atmospheric pressure an azeotrope with 55% (volume) of benzene is found. Furfural is commonly used as an entrainer to overcome this azeotrope and to increase the driving force for separation of benzene from cyclohexane. In the hybrid scheme, a membrane made of carboxymethyl cellulose and sodium alginate [42] is used to purify the distillate product from the distillation column from 88.8% (mole) to 99.5% (mole) cyclohexane. The operating conditions and design details of the membrane unit are given in Table 3. For the same degree of separation, the performance of a conventional extractive distillation process is compared with the proposed hybrid scheme. Both cases are simulated using Aspen Plus v9 and the designs along with the simulation results are shown in Fig. 7. The conventional extractive distillation process requires 43.5 Gcal/h of reboiler duty, while the proposed hybrid scheme requires only 25 Gcal/h. Thus, for the same degree of separation, use of the hybrid separation scheme results in savings of 42.5% reboiler duty and 34.83% reduction in the amount of the entrainer used (Table 3).

Table 3 Membrane design data

	Value	Units
Flux	0.713	kg/m2 h
Thickness of the membrane	50	μm
Separation factor of benzene	212	
Membrane area, calculated	3400	m2

The significance of the hybrid scheme can be understood by considering that there are currently more than hundred thousand operating distillation columns in the chemical and related industries on earth, and taking into account that they are energy intensive, between 10 and 50% of their energies can be potentially reduced through the proposed hybrid scheme. This alone would indeed lead to a significant reduction of energy consumption in the chemical and related industries.

Energy reduction and CO_2 mitigation by process integration

Another option for energy and CO_2 mitigation is the integration of different tasks or processes with the objective of minimizing resource usage and emissions. The objectives have been realized by developing optimal heat and mass exchange networks, water conservation networks, waste water minimization networks using different methodologies [43, 44]. Process integration coupled with intensification can give better solutions than traditional approaches. In this section, the advantages of process integration are highlighted with recent examples from the literature.

Tilak and El-Halwagi [45] proposed an eco-industrial park configuration for CO_2 intensive industries. Calcium looping (CaL) technology, known to be a potential option for CO_2 capture, is integrated with CO_2 emitting operations. A CO_2 rich stream from Calcium looping is used as a feedstock for product. The best possible configuration is identified from the available combinations shown in Fig. 8, based on a techno (energy consumption and CO_2 purity) economic (cost of CO_2 capture, CO_2 sale revenue, electricity sale revenue and return on investment) evaluation of CO_2 source integrated with CaL technology. A techno-economic analysis reveals that integration of a gas to liquid (GTL) plant with CaL technology has a high rate of return. The downstream integration performance is evaluated and recommended for use of CO_2 captured from a GTL plant as a feedstock for production of acetic acid, polymers and methanol.

Energy-process intensification

The objective of process intensification is to generate new process alternatives consisting of hybrid/integrated/intensified options at different scales (unit operation, task and/or phenomena) that also satisfies the same set of process specifications but subject to a new set of targets for improvement with respect to the process performance criteria, e.g. economy and efficiency (energy-water consumption, environmental impact,

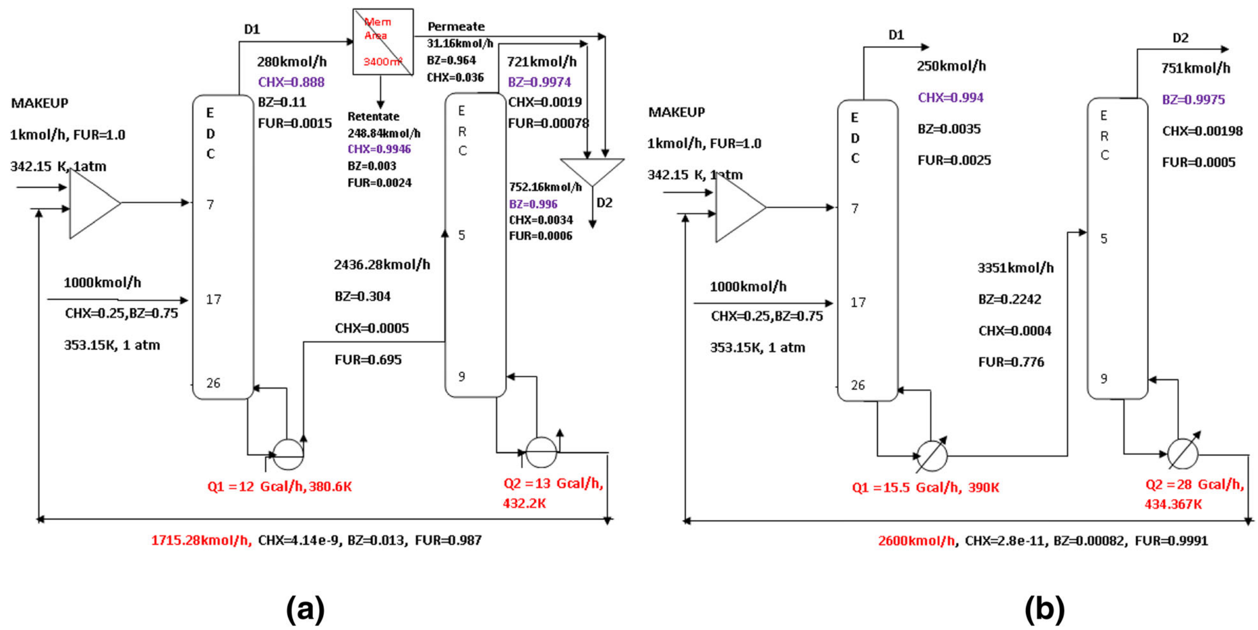

Fig. 7 Simulation results for Benzene-Cyclohexane separation task using (**a**) Hybrid separation scheme with extractive distillation coupled with membrane and (**b**) Conventional extractive distillation

waste, safety issues, and, number of unit operations). The development and implementation of alternative energy conversion techniques using solar energy, prominent due to its abundance, has been reported by Gencer et al. [46] Other intensification options to generate more sustainable energy efficient alternatives have been reported by Babi et al. [47] and recently, Landero et al. [48] illustrated the application of a phenomena based intensification method to minimize equipment units as well as targets for improvements to a process to produce dioxolane products.

Green technologies for efficient supply of energy

In this section, similar integration and reduction techniques discussed above for chemical and petrochemical industries, are employed for biomass-based processes

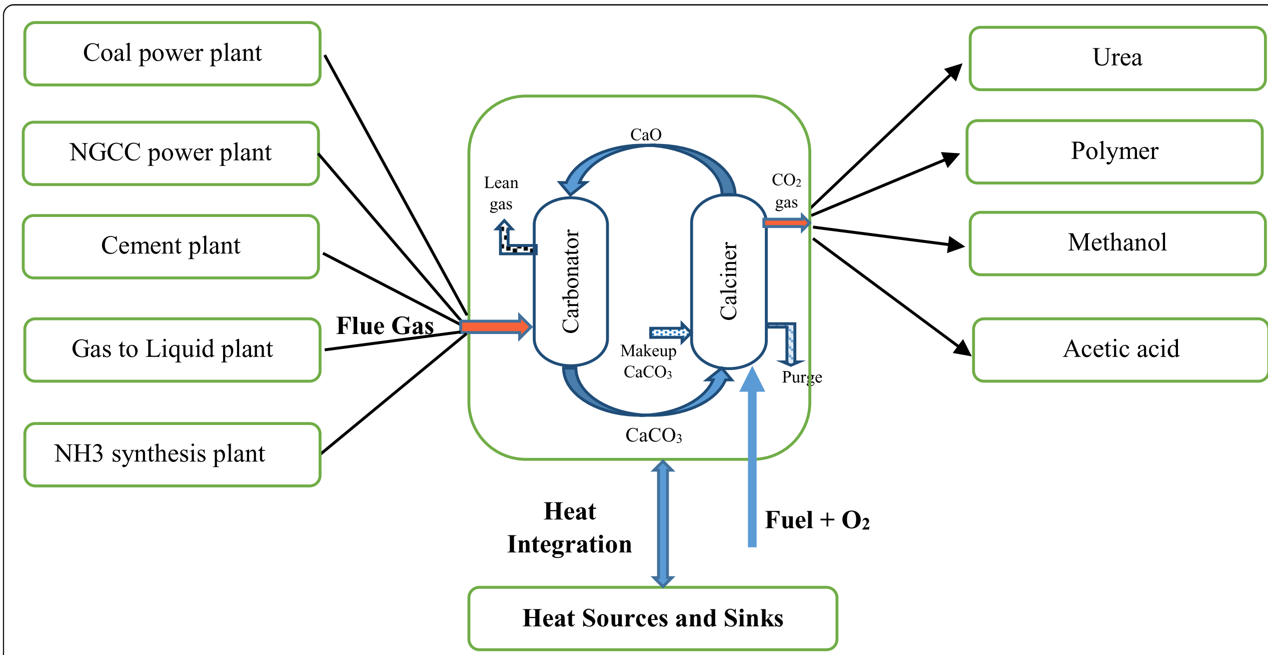

Fig. 8 Schematic representation of case study

and to the use of non-fossil sources of energy. Several examples of developed technologies that can make a significant impact to the energy and CO_2 management issues are highlighted below. The first example reports the results from the application of a new technology, while the other examples report the evaluation of other technologies in terms of their potential to improve the process sustainability.

Heat integration in bioethanol purification process: New application example

The advantage of energy integration is highlighted through a simple case study [49] involving the separation processing steps in bioethanol production. Figure 9a shows the conventional process flowsheet without heat and mass integration for the separation of feed mixture of 12% (mass) ethanol and 88% water into high purity products. The process requires 215 kW of reboiler energy and cooling water at 14 °C to remove the 164 kW of waste heat from different streams. The process with energy integration has resulted in 16.74% savings in reboiler duty and 22% savings in condenser utility as shown in Fig. 9b.

The energy demand for the integrated separation process can be met from non-fossil energy resources to make the process more sustainable. For example, the total required reboiler heat energy of 179 kW in the bioethanol separation process as shown in Fig. 9b is integrated with different energy resources (electricity, biomass and solar power) and the analysis results are given in Table 4. The analysis includes the resultant CO_2 emissions in case of electrical power and sugarcane bagasse along with the area required in case of solar thermal power.

Energy efficient sustainable conversion of biomass

Almost any kind of fossil fuel can be substituted by solid, liquid and/or gaseous biofuels produced by biomass based chemical conversion processes, thereby reducing the associated greenhouse gas emissions [3]. Three interesting developments are highlighted here. I) A method for synthesis of processing routes for conversion of biomass to useful chemicals and biofuels has been developed by Bertran et al. [34], which takes into account the location and amount of available biomass, the chemical (product) demand, the local CAPEX and OPEX as well as transportation costs. With this method and associated computer aided tools, it is possible to determine more sustainable processing routes for conversion of a given biomass at a specific geographical location to a set of desired products for sale at other locations, according to their demand. According to one scenario, a sustainable option is to ship cassava rhizome and bagasse from Thailand to Canada for pre-treatment of the biomass, and perform the actual production of fuel-grade ethanol in Mexico and sell thee product in USA. Changing the prices and/or constraints, a totally different scenario is obtained. Note that production of chemicals reduces the use of non-renewable resources for their production, thereby making the bio-conversion route more sustainable. II) Another option to convert biomass to energy is proposed by Girones et al. [50], where use of a biomass gasifier to convert lignocellulosic biomass such as wood into syngas that can be used in a Solid Oxide Fuel Cell (SOFC) to produce heat and electricity has been highlighted. III) Sharma et al. [51] compared many biomass conversion options considering the complete energy conversion pathway, from the resource to the supply of energy services. The comparison, which includes 56 scenarios, is performed by evaluating the CO_2 abatement potential of integrating these different pathways into a national energy system. Results show that biofuels can allow for an overall better performance in terms of avoided CO_2 emissions compared to direct combustion of biomass. To exploit this potential, however, it is necessary to link the production of biofuels to a wider deployment of the corresponding efficient end-use technologies.

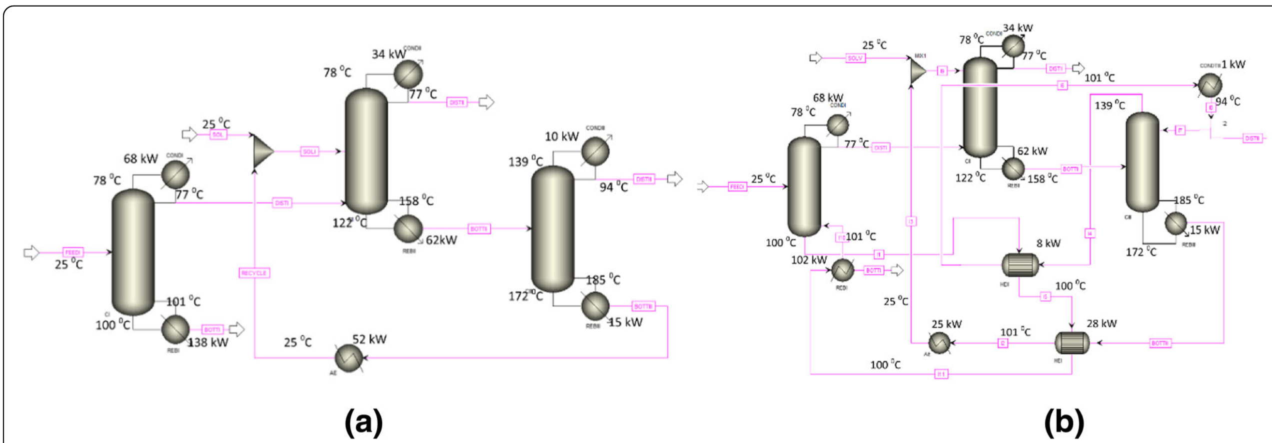

Fig. 9 Bioethanol separation process a) without heat integration b) with heat integration

Table 4 Analysis on the use of different energy resources

Source of energy	Electrical power	Sugarcane bagasse[#]	Solar thermal power
Process	Electric heating boiler	Direct heating	Electric heating boiler
Efficiency of the process:	90%	70%	90%
Total power required (kW)	199	256	199
Amount of fuel/solar energy required (kW)	663[*]	256	925.6**
Calorific value of fuel	Coal[&]: 15830 kJ/kg	16,450 kJ/kg	–
Amount of fuel required	150.7 kg/h	56.02 kg/h	
Amount of CO2 released	150.6 kg/h	91.4 kg/h	
Total solar collector field area			4547 m2

* 30% efficiency for coal fired power plant (Suresh, et al. [79]); ** 21.5% efficiency for solar power plant (Reddy, et al [80]); [&] Coal properties (Suresh, et al [79]); # Biomass properties (Xie, et al [81])

Application of green energy technology

Decarbonization of the power sector is a prime remedial action to secure a maximum 2 °C rise of atmospheric temperature by the twenty-first century. According to the 2 °C scenario (2DS), the global power sector should have a net zero CO_2 emission by 2060. This would require 74% of global power generation from renewables, 7% from fossil fuels with CCS, 15% from nuclear and remaining 4% from natural gas [5]. Currently, two main approaches can be adopted for the use of green energy in the industrial sector: (a) direct use of electricity/heat energy from renewables, (b) energy from fossil fuels integrated with CO_2 capture and utilization. Figure 10 shows the characteristics of the sustainable energy generation system [52]. Use of clean electrical energy from sustainable sources can create a carbon neutral industrial atmosphere. Industrial processes, which cannot be electrified can reduce their CO_2 emissions by increasing the energy efficiency and using energy from renewables. In this section a brief analysis of the usability of green energy technologies is presented.

Energy from renewables including solar PV (photo voltaic), wind, hydropower, bioenergy, geothermal, and concentrating solar power can have low carbon footprint. Power generation using solar PV showed a record growth of 34% in 2017 and new additions to the capacity are on track as per the 2DS [53]. By 2020 the global solar PV installed capacity is expected to be 725 GW [54] and it is anticipated that the average levelized cost of electricity (LCOE) is expected to be about 13.3 US cents / kwh and by 2050 the LCOE will be about 5.6 US cents /kwh, which will be an economically feasible option [55, 56]. At present in some regions the energy from renewables is cheaper than the energy from fossil fuels. For instance: i) in Iceland and other specific locations, the use of geothermal hot water is less expensive than coal or oil heated water for heating buildings; ii) in the US Pacific Northwest hydropower is more economical than other alternatives [57]. However, capacity additions in renewable power sectors need more attention to be aligned with sustainable targets. In addition, the energy from renewables is often intermittent in nature and mature technologies are not available to meet the base load demand. For instance, currently, the progress of solar power utilization is in line with the sustainability targets. The power generation is expected to increase to 27×10^8 MWh by 2030. To harvest the solar power, modern technology requires approximately 0.02 km^2 of land for 1 MWh power output [58]. By 2030, 54×10^6 km^2 of land will be required, which is 36.25% of the total land area of the planet, to meet the projected capacity. To meet the sustainable targets by the twenty-first century, the land required by renewable power plants will be more than 50% of the land available on earth, which is not a viable option. Therefore, to meet the baseload demand, increase of renewables-based power production capacity without significant improvement in energy efficiency can pose a serious threat to ecosystems. As an alternative to this, energy from fossil fuels integrated with CO_2 capture and nuclear power integrated with zero hazardous emission could lead to potential green energy technologies and sustainable energy resources to meet the global base load demand in the near future. At the end, a judicious mix of use of fossil fuels with CO_2 capture, nuclear power with zero hazardous emission and renewable energy can be a more sustainable and viable option rather than using a single source of power.

Power from fossil fuels combined with CO_2 capture

Today around 39.9% of the power industry uses coal while natural gas contributes around 22.6% for electricity generation [59]. However, besides being one of the most economical options for large scale electricity generation, these conventional power plants also contribute huge amounts of greenhouse gas emissions. Therefore, performance enhancement of fossil fuel based power plants through increased efficiency and thereby reduced fuel consumption and gas emissions has received much research interest [60]. Currently, thermal efficiency of modern power plants range between 43 and 55% for subcritical and supercritical coal-fired power plants,

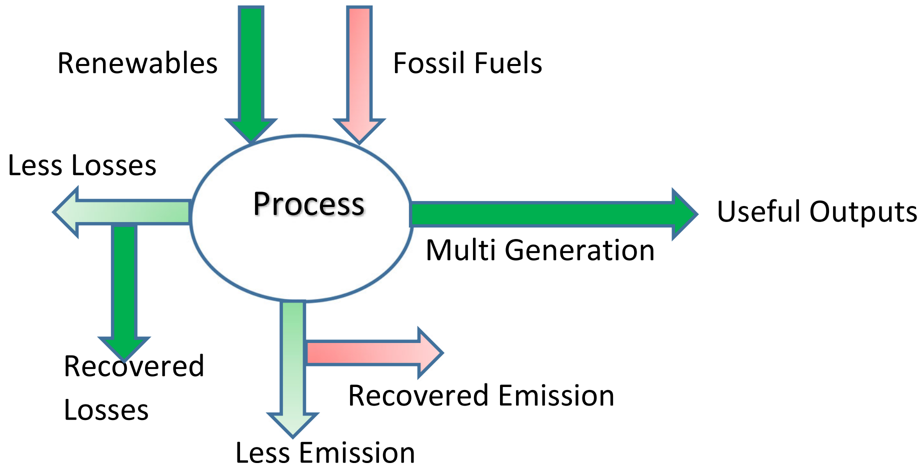

Fig. 10 Sustainable energy generation system

while it is 62% for combined cycle thermal power plants [59]. However, to achieve sustainability, the improvement in conversion technologies need to be matched with CO_2 emissions reduction technologies. During the last decade, integration of CO_2 capture technologies with power generation plants with the goal to transform thermal power plants into sustainable technology has received much attention. A search of the literature between 2007 and 2017, found 28,000 patents and 5000 scientific documents. Among these, the primary CO_2 capture technologies are the chemical absorption and adsorption techniques [61]. Currently CO_2 capture using amines is considered the most mature and economical [62, 63] technology, while the chemical and calcium looping combustion technologies are considered emerging CO_2 capture technologies [64, 65]. An excellent review of CO2 capture technologies is given by Yuan et al [66] For a truly sustainable solution, however, CO2 capture needs to be further integrated with sequestration and/or utilization.

Future perspectives and conclusions

For the last two decades, research has been focused on development of sustainable energy utilization methods in energy intensive sectors, such as the transportation and industrial sectors. In order to arrest the CO_2 emissions from the transportation sector, use of electric vehicles has been considered as a very promising option [53]. To realize this option, electricity demand needs to be met from sustainable sources of energy supply, such as solar, wind and fossil energy integrated with CCS/CCU.

Since the industrial revolution, the manufacturing sector has been evolving with new technologies at a rapid pace and delivering a wide variety of chemicals-based products needed by modern society. The demand for raw materials and energy has therefore been increasing continuously with increasing industrial productivity. However, to curtail the associated industrial CO_2 emissions within a sustainable target, serious efforts are needed to improve the energy efficiency of energy intensive manufacturing processes. Technologies to convert renewable energy resources to meet the energy demands need to be improved and made economically feasible. The complex and energy-intensive processes need to be replaced by more sustainable alternatives that are able to use energy of different qualities and forms. In chemical and related industries, PSE techniques such as process intensification and process integration have been playing a key role in generating new, innovative, integrated, more sustainable and energy efficient process alternatives. Innovations in some of the potential areas can open up new avenues for development of energy efficient industrial processes: (i) catalysis – objective: development of new catalysts such that the same conversion tasks can be performed at a much lower temperature and/or energy demand. Notable contributions in this area include: Davda et al. [67] proposed a single step low temperature (128 °C) aqueous-phase reforming process for H_2 production from biomass-derived oxygenated hydrocarbons using metal catalyst. Recently, Yao et al. [68] synthesized a catalyst consisting of layered gold clusters on molybdenum carbide (MoC) nanoparticles, which enables the water gas shift reaction at 150 °C. Yabe et al. [69] observed that La-doped Ni/ZrO_2 catalyst in the presence of 6.9 w electric field equivalent at 423 K has high dry reforming of methane activity with about 77.2% CH_4 and 87.6% CO_2 conversions. (ii) hybrid separations – objective: development of separation techniques based on exploiting the available driving force, which is inversely proportional to energy need. Recent developments in this direction include heat pumps [70], dividing-wall columns, [36] heat-integrated distillation column [37], multi-effect distillation [39], membrane distillation [40] and hybrid schemes with membrane modules

[41]. Due to their low price and easy availability, humans will still rely mainly on fossil fuels for the foreseeable future. Therefore, improvements should be placed on advanced energy generation and CO_2 capture technologies to minimize CO_2 emissions. To this end, technologies such as advanced gasification systems and chemical looping combustion (CLC), which has inherently zero net CO_2 emissions and high energy efficiency [71, 72]. Additionally, integration of energy supply and demand at different levels can result in a more sustainable and optimal energy utilization. Thermal integration at unit level uses the latent stream energy content and minimizes the external utility requirement. Whereas application of combined cooling, heat and power system integration at process/site level can be more advantageous than thermal integration by means of interaction between the core processes and utilities. Energy integration at region level has a high potential to address the CO_2 emission problem at bulk scale by re-allocating the available sustainable energy resources. To perform energy integration at the region level, collection of energy demand and supply (existing and potential for addition) data and development of appropriate models is a good starting point.

This paper has analyzed available data related to the current status of energy resources, energy consumption by various sectors and especially focused on the industrial sector, where chemicals and related industries are the largest consumers. Although many promising technologies with respect to reduction of energy and CO_2 emission management are available, their implementation and use is still lacking. Therefore, urgent action still needs to be taken if the planet's temperature increase is to be controlled and kept to the agreed limit of 2 °C. That is, a wider application of the most promising technologies that can make a significant impact is necessary. For example, replacement of all currently operating distillation columns with hybrid schemes that require minor changes and investment but promise significant energy reductions could be considered as a bold step in the right direction. Opportunities exist to tackle the challenges in a systematic and coordinated manner. The chemical and related industries offer these opportunities because they are energy intensive and therefore are prime targets for application of new and innovative technologies that are more sustainable. In this respect, process alternatives that lead to significant improvements need to be determined. Model based computer aided techniques that can quickly identify the promising alternatives must be employed for rapid and reliable resolution of the grand challenges facing us.

Abbreviations
CaL: Calcium Looping; CCHP: Combined Cooling, Heating & Power; CCS&U: Carbon Dioxide Capture, Sequestration & Utilization; CHP: Combined Heat and Power; DMA: Direct Methane Aromatization; GCC: Grand Composite Curve; IEA: International Energy Agency; IEO: International Energy Outlook; MILP: Mixed Integer Linear Programming; MINLP: Mixed Integer Non-linear Programming; ODC: Oxygen Depolarized Cathodes; PSE: Process Systems Engineering; SDS: Sustainable Development Scenario; SOFC: Solid Oxide Fuel Cell

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