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Introduction

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It is expected that in the current century, the theme "energy" will become increasingly more important and will pose some serious challenges to our society and our way of living, but it may also create opportunities.

On the one hand, the combination of a rapidly growing world population and increasing energy consumption per capita requires large investments to secure sufficient energy supply at affordable prices. On the other hand, fossil fuel reserves are shrinking, while the transition toward a world economy based on energy supply via sustainable or renewable resources is still in its infancy. According to the World Energy Outlook 2013 of the International Energy Agency (IEA), the world energy demand will increase by more than 30% by 2035 (compared with 2011) and the demand for oil alone will still be more than 57% in 2035. Oil and gas reserves are increasingly concentrated in a few countries that control them through monopoly companies. The dependence of Europe on imported oil and gas is growing: we import 50% of our energy, and it will be 55% by 2035 (Bp Outlook 2035), if we do not act.

The relevance of this issue is even higher when one relates the increase in anthropogenic CO_2 emissions by the use of fossil fuels to the evident changes in the Earth's climate. The International Panel on Climate Change (IPCC) has collected results of substantial research efforts to obtain a comprehensive scientific framework describing the evolution of the climate over very long time periods, the observed deviations from this behavior in recent times, the interpretation of both natural and anthropogenic causes and their effect on the increase of the greenhouse effect, the consequences of global warming in the past, present and future and possible solutions to combat further climate changes. In its 2013

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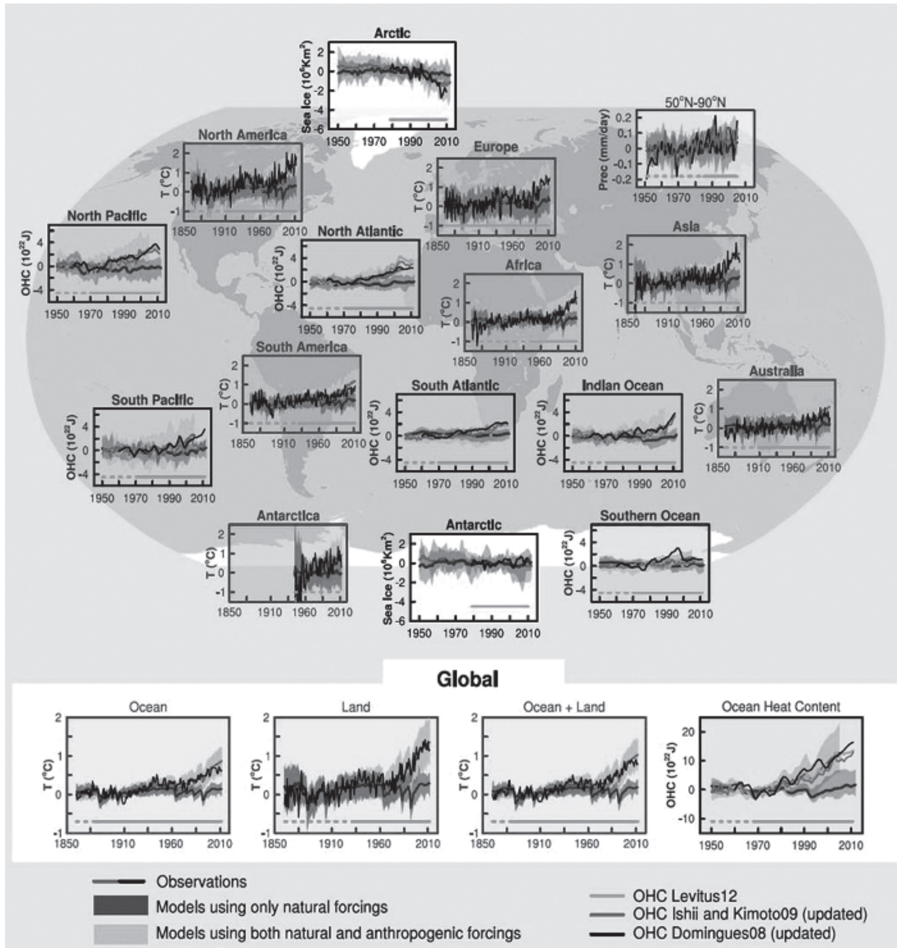

Figure 1.1 *Detection and attribution signals in some elements of the climate system, at regional scales (top panels) and global scales (bottom four panels). Brown panels are land surface–temperature–time series, green panels are precipitation–time series, blue panels are ocean heat content–time series and white panels are sea ice–time series. Observations are shown on each panel in black or black and shades of grey. Blue shading is the model time series for natural forcing simulations and pink shading is the combined natural and anthropogenic forcings. The dark blue and dark red lines are the ensemble means from the model simulations. All panels show the 5–95% intervals of the natural forcing simulations and the natural and anthropogenic forcing simulations. (*Source*: Extracted from the IPCC report 2013) (For a color version of this figure, please see color plate section.)*

Assessment Report, IPCC conclude that (Climate Change 2013: The Physical Science Basis), see Figure 1.1:

> *"From up in the stratosphere, down through the troposphere to the surface of the Earth and into the depths of the oceans there are detectable signals of change such that the assessed likelihood of a detectable, and often quantifiable, human contribution ranges from likely to extremely likely for many climate variables."*

According to IPCC, the effect of human activities on changes in the climate is very likely to have been dominating natural variations (due to, e.g., variations in solar irradiance) especially in the past 50 years. Since the beginning of the industrial revolution, the concentrations of the relevant greenhouse gases (especially carbon dioxide, methane, nitrous oxide, and halocarbons) have increased substantially and now by far exceed natural ranges encountered in the past 650,000 years [1].

On the short term, significant reductions of carbon dioxide emissions may be attained from energy savings, for example, via efficiency improvements both in power production and consumer products and as a consequence of increased public awareness. However, strong economic growth anticipated in especially the developing countries is expected to impede a net decrease in anthropogenic emissions. On the longer term, the use of fossil fuels for energy supply will need to be phased out not only to stabilize greenhouse gas concentrations but also to avoid shortages in raw materials for the production of, for example, bulk chemicals.

The transition towards a world economy based on energy supply via sustainable sources such as wind-, hydro- and solar energy, or nuclear power (of which fission still suffers from a bad public image caused by concerns over nuclear waste and proliferation, whereas fusion has so far failed to live up to its potential) is therefore expected to be a lengthy process that cannot be expected to be solely responsible for the stabilization of atmospheric greenhouse gas concentrations in this century. Rather, a combination of many of the mitigation alternatives will need to be adopted to significantly curb CO_2 emissions.

In this respect, novel concepts based on process intensification can help to reduce CO_2 emissions and can lead the transition towards a more sustainable energy scenario. Indeed, according to Ramshaw [2], process intensification is a strategy for making dramatic reductions in the size of a chemical plant so as to reach a given production objective. As such, applying process intensification to the energy sector can result in a dramatic decrease in the production of wastes including greenhouse gas emissions.

According to Stankiewicz and Moulijn [3], the whole field of process intensification can be classified into two main categories:

1. Process-intensifying equipment:
   These include novel reactors and intensive mixing, heat-transfer and mass-transfer devices, and so on.
2. Process-intensifying methods:
   These include new or hybrid separations, integration of reaction and separation, heat exchange, or phase transition (in multifunctional reactors), techniques using alternative energy sources (light, ultrasound, etc.) and new process-control methods (like intentional unsteady-state operation).

Clearly, as also indicated by Stankiewicz and Moulijn, there is a big overlap between the two areas. For instance, membrane reactors are an example of process-intensifying equipment (novel reactor) making use of process-intensifying methods (integration of reaction and separation).

Since the "invention" of the term *process intensification*, many articles and books appeared on the same topic. An interested reader is referred to the book of Reay *et al.* [4] for an overview of the various process intensification methods. In the present book, a selection of different, novel process intensification methods and reactors are presented and discussed with the focus on sustainable energy conversion.

In particular, in Chapter 2 the development of a new cryogenic separation technology based on dynamic operation of packed bed columns is described. When it is possible to exploit the cold available at, for example, LNG regasification stations, this new technology could be used as an efficient post-combustion CO_2 capture technology. In the chapter, the technology is described to freeze-out CO_2 from flue gases at atmospheric pressures. The dynamic operation and the effects of the operating conditions have been analyzed in detail using modelling and an experimental proof of principle at laboratory scale and small pilot scale is provided. Finally, a techno-economic analysis shows the great potential of the technology over other post-combustion capture processes such as amine scrubbing and membrane separation, when cold duty is available at low prices or when high CO_2 capture efficiencies are required. This makes the cryogenic technology also particularly interesting as an auxiliary unit downstream of other post-combustion technologies.

Chapter 3 describes the application of membrane reactors in pre-combustion CO_2 capture technologies. Different membrane reactor configurations are described, among which the fluidized bed membrane reactor configuration seems to have the most potential. In this concept, hydrogen perm-selective membranes are submerged in a fluidized suspension. Thus, mass and heat transfer coefficients are much improved compared to packed bed membrane reactor configurations (decreasing problems in heat management and concentration polarization), while maintaining a relatively large amount of catalyst combined with a relatively low pressure drop in comparison with micro-membrane reactors. The chapter also describes a hybrid concept integrating both membrane reactors and chemical looping combustion for autothermal operation with integrated CO_2 capture. With this new concept, high hydrogen efficiency can be obtained at lower temperatures compared with other concepts, while the amount of membrane area required is kept to a minimum.

Chapter 4 focuses on the possibility to apply high-temperature oxygen-selective membranes in oxy-fuel power production systems. These perovskite-like or mixed ionic electronic conducting materials present an infinite perm-selectivity for oxygen compared with other gases and can thus be used to separate oxygen from air at high temperatures. The chapter describes the main features of oxygen selective membranes, their production methods and their integration in membrane (reactor) modules. The chapter also reports on the progress of research projects on oxygen selective membranes.

A different kind of oxy-combustion can be achieved by exploiting the air separation through a solid material that is alternating oxidized (with air) and reduced (with a fuel). This solid material is called oxygen carrier and is the “catalyst” of a new concept called chemical looping combustion. Chapter 5 describes chemical looping combustion (CLC) concepts for power production. The oxidation and reduction stages can be achieved with different reactor technologies. In particular, it is possible to circulate the solid material between two fluidized bed reactors, where one reactor operates as oxidation reactor (air reactor) and a second reactor operates as reduction stage (fuel reactor). Another possibility is to keep the solid in fixed position and to alternately switch the gas feed streams; in this case, the concept is based on dynamically operated packed beds. Finally, the solid can be kept in a fixed position and the reactor can be rotated. The chapter reports all the possible configurations for CLC and compares the efficiencies of different concepts when exploited for power production.

Another interesting concept that can also be used for power production with integrated CO_2 capture is sorption-enhanced fuel conversion and is described in Chapter 6. In this concept, a solid sorbent is used together with the catalyst such that the CO_2 produced during the reforming (or water-gas shift) of a fuel can be directly captured and separated, while the other products, often hydrogen, can be used for downstream power production. Also with sorption-enhanced processes, the efficiency of the CO_2 capture can be significantly increased, because the hydrogen is generally produced at high pressure, whereas in many other concepts, such as the membrane reactor concepts presented in Chapter 3, the hydrogen is produced at lower pressures. On the other hand, the CO_2 pressure is higher in membrane processes compared with sorption-enhanced processes. The selection between these two concepts is thus related to many different parameters, and the efficiency should be evaluated separately for each individual case.

Chapter 7 reports on the hydrogen production for fuel cell applications. Also for this application, membrane reactors are described in detail. The need for smart reactor designs in order to reduce or circumvent concentration polarization (or bulk-to-membrane mass transfer resistances) and improve the heat management is pointed out, which places stringent requirements on membrane stability, catalyst activity, sealing technology, support materials and module design. The chapter describes the ongoing research on micro-structured membrane reactors which will be a step forward towards low cost and high productivity units for hydrogen production.

All these chapters describe the smart use of reactor design and process integration to increase the efficiency and reduce the emissions when using fossil fuels as energy source. Of course, intensified systems can also be used for bio-based energy sources. Chapter 8 reports the possibility to convert biomass into substitute natural gas. The chapter describes how both packed beds and fluidized bed reactors can effectively be used to improve the methanation reaction so that the products of biomass gasification can be converted into a more sustainable methane stream.

Chapter 9 describes how to efficiently make use of a salinity gradient for power production. This is a completely CO_2-free power production system, so that the concept is often referred to as blue energy. The concept is based on the fact that chemical potential is associated with a difference in salt concentration, so that electric power can be produced by exploiting the salinity gradient between freshwater of rivers and seawater. When exploited at large scale, this concept can supply a large part of the electricity required worldwide. However, the concept is not that easy as conventional hydropower electricity production. The chapter describes the fundamentals of the salinity gradient technology and the attainable energy efficiencies associated with this energy conversion technology.

Chapter 10 describes how process intensification can be applied to efficiently make use of the most abundant energy source: solar energy. The question is addressed whether an intensified process layout can increase the potential of solar process heat and its efficiency. The chapter describes how to make efficient use of solar heat by designing the heat profile in a certain process, where the importance of process modeling in this respect is stressed.

Finally, Chapter 11 reports on intensified processes for biomass utilization. In particular, the authors describe the broad field of power and combined heat and power (CHP) generation from biomass: more specifically, advances in biomass gasification technology aimed at increases in overall conversion and efficiency and hence in a decreased cost of electricity. Poly-generation strategies (for combined heat, power and chemical production applications) are also considered, with particular reference to recent technological innovations in hot gas cleaning and conditioning; these have been developed to achieve the required improvements in syngas quality and have been validated under industrially relevant conditions.

We surely know that many other intensified processes can be designed for efficient power production, or in general for energy conversion. We hope that the content of this book will stimulate the design, implementation and testing of novel integrated reactor concepts for a more sustainable energy future.

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