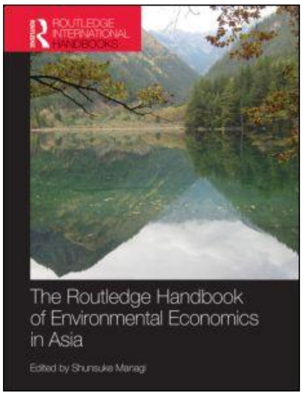

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Shunsuke Managi

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ENERGY AND CLIMATE CHANGE

Takayuki Takeshita

1. Introduction

Climate change is one of the most challenging issues facing the world today. Global awareness of the phenomenon of climate change is growing rapidly, and an increasing number of policy actions are underway to tackle climate change. However, it is indicated that current legislative plans in the aggregate are not sufficient to avoid dangerous climate change (e.g., Riahi et al., 2012). This emphasizes the need for examining quantitative strategies for climate change mitigation that can help achieve global climate stabilization at a safe level.

The energy sector is currently by far the largest source of greenhouse gas (GHG) emissions, accounting for more than two-thirds of the global total (around 90 percent of energy-related GHG emissions being CO_2 and around 9 percent being CH_4) (IEA, 2013). Without policy interventions to achieve global climate stabilization, the energy sector would account for an ever-increasing share of global total GHG emissions (IIASA, 2012). Accordingly, the energy sector has a crucial role to play in tackling climate change.

Thus, the aim of this chapter is to shed light on the question of how future energy systems can meet a global climate stabilization target of 2 °C above pre-industrial levels. For this purpose, this chapter introduces a sustainable energy pathway meeting multiple sustainability goals, such as climate change mitigation over the period 2010–2100 for the whole world and for three developing Asian regions (i.e., Centrally Planned Asia, South Asia, and Other Pacific Asia),[1] which is presented by Riahi et al. (2012) and called the illustrative GEA-Mix pathway.[2] For comparison purposes, a corresponding counterfactual no-policy baseline energy pathway, which is also taken from Riahi et al. (2012) and called the GEA counterfactual pathway, is shown for the whole world and for the three developing Asian regions. These two energy pathways were developed using an integrated assessment modeling framework called MESSAGE[3] (Messner and Strubegger, 1995; Messner et al., 1996; Riahi et al., 2007).

The rest of this chapter is organized as follows. Section 2 describes the methodology for the development of the two energy pathways shown in this chapter. In Section 3, the two energy pathways are shown over the period 2010–2100 for the whole world and for the three developing Asian regions. By comparing the sustainable energy pathway (i.e., the illustrative GEA-Mix pathway) with the no-policy energy pathway (i.e., the GEA counterfactual pathway), the question of what types and levels of demand- and supply-side energy system transformations are required to meet the stringent climate stabilization target is explored. Section 4 concludes the chapter.

2. Methodology for the development of the GEA pathways

2.1 GEA pathways

In addition to the GEA counterfactual pathway, Riahi et al. (2012) present three GEA pathway groups meeting multiple ambitious sustainability goals to represent different emphases in terms of the demand- and supply-side transformations of the energy systems, which were labeled as the GEA-Efficiency, GEA-Mix, and GEA-Supply pathway groups. Although the same socioeconomic and demographic assumptions, such as those on gross domestic product (GDP) and population, are used for all the GEA pathways (including the GEA counterfactual pathway), each pathway group varies substantially with respect to levels of energy demand, leading to pathway groups of low energy demand (GEA-Efficiency), intermediate energy demand (GEA-Mix), and high energy demand (GEA-Supply).

Such different levels of energy demand represent a difference in the assumption about the degree to which efficiency improvements can limit energy demand growth. Low levels of energy demand increase flexibility on the supply side of the energy systems, and vice versa, a more rapid and radical transformation of the supply side increases flexibility on the demand side. Within each pathway group, the alternative choices of transportation system transformation (conventional or advanced) and the portfolio of supply-side options (full or restricted) generate a wide range of alternative GEA pathways with different supply-side characteristics.[4]

For each of the three GEA pathway groups, one illustrative case was chosen that most clearly reflects the main characteristics of the respective group. Of the three illustrative GEA pathways, the illustrative GEA-Mix pathway is regarded as intermediate with respect to many scenario characteristics, such as the emphasis on efficiency improvements and the pace of supply-side transformations. For these reasons, the illustrative GEA-Mix pathway[5] was selected as the sustainable energy pathway in this chapter.

2.2 Sustainability goals of the three GEA pathway groups

All the three GEA pathway groups are designed to describe transformative changes in energy systems required for simultaneously meeting the following four energy-related sustainability goals: (1) to improve energy access, (2) to reduce air pollution and to improve human health, (3) to avoid dangerous climate change, and (4) to improve energy security. These four sustainability goals are defined in terms of specific targets and timelines, which are regarded as ambitious, and are the fundamental drivers of the demand- and supply-side transformations of the energy systems described in the three GEA pathway groups.

For the first and second goals, it is assumed that almost universal access to electricity and clean cooking fuels should be achieved by 2030 and that compliance with the World Health Organization (WHO) air quality guidelines should be achieved for the majority of the world population by 2030 with the remaining populations staying well within the WHO Tier I–III levels by 2030. For the goal of avoiding dangerous climate change, it is assumed that the global mean temperature increase should be limited to 2 °C above pre-industrial levels with a likelihood of more than 50 percent.[6]

On the other hand, energy security concerns typically relate to energy systems' robustness, sovereignty (often quantified as net import dependency in a region), and resilience (often quantified as the diversity of types of primary energy sources in a region) (Cherp and Jewell, 2011). In the three GEA pathway groups, the sovereignty and resilience concerns are addressed, while the robustness concerns are not. The three GEA pathway groups incorporate the sovereignty dimension by limiting energy trade as a fraction of total primary energy supply at a regional scale, but the resilience dimension is not a direct limitation in them.

2.3 Overview of the integrated assessment modeling framework MESSAGE

MESSAGE is a systems engineering optimization model, which represents the whole energy system from resource extraction, imports and exports, conversion, distribution, and the provision of energy end-use services. For the development of the GEA pathways, important inputs to the MESSAGE model are a harmonized set of technical, economic, and environmental parameters, which include reference energy demand (calculated as the product of reference GDP and reference energy intensity), the availability and extraction costs of energy resources, the efficiency of technology options, their capital and operating and maintenance costs, and their pollutant emission factors.

Given these inputs, the MESSAGE model obtains optimal results by minimizing the sum of the discounted costs under various constraints, including those imposed on the multiple sustainability goals (described in Section 2.2). Examples of model results include: price-induced changes in energy demand, deployment of demand- and supply-side measures, primary energy supply by energy source, final energy consumption by fuel, emissions of air pollutants and GHGs, energy system investments, and costs of meeting the sustainability goals. In the model results, GHG emissions reduction is achieved when and where it is most cost-effective.

Table 7.1 shows the regional definition of the three developing Asian regions. In addition, eight world regions are defined in the MESSAGE model. They are: North America, Western Europe, Pacific OECD, Central and Eastern Europe, the Former Soviet Union, Latin America, the Middle East and North Africa, and Sub-Saharan Africa. Detailed scenario data for the individual GEA pathways for these 11 world regions are publicly available in the GEA database (IIASA, 2012).

Table 7.1 Regional definition of the three developing Asian regions

Names of the regions	*Countries included*
Centrally Planned Asia	Cambodia, China (incl. Hong Kong), Democratic People's Republic of Korea, Laos, Mongolia, Vietnam
South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
Other Pacific Asia	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan, Thailand, Tonga, Vanuatu, Western Samoa

3. Interpretation of the results of the sustainable energy pathway

3.1 Demand-side energy system transformations

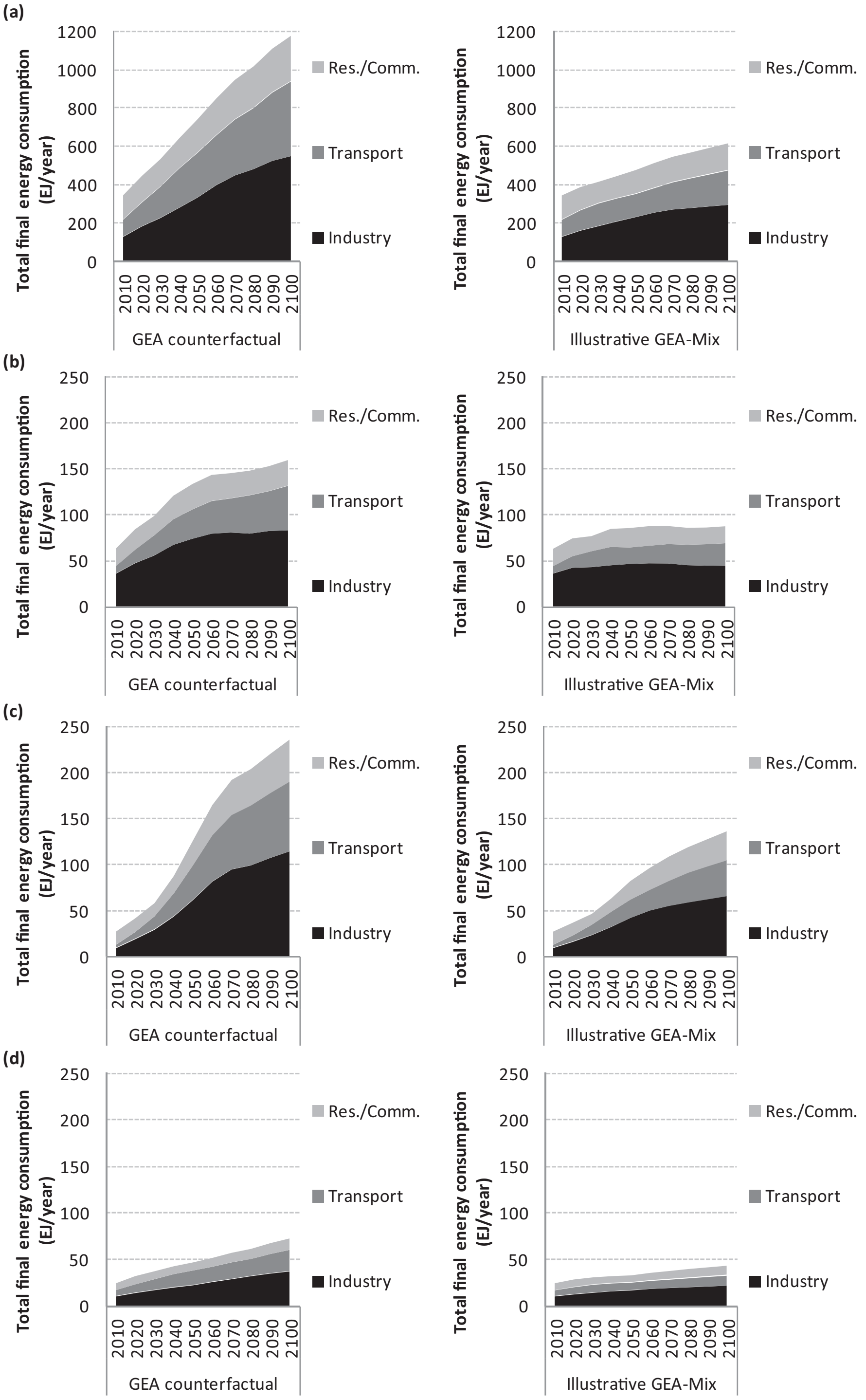
The following three approaches are explored in the three GEA pathway groups as a means of reducing final energy demand: (1) improving technological efficiency, (2) changing the structure of energy services demand (e.g., modal shift), and (3) reducing the level of energy services demand (e.g., mobility demand reduction). The three GEA pathway groups assume that the rapid and pervasive introduction of highly energy efficient end-use technologies will play a central role in reducing final energy demand throughout the time horizon to 2100, which is enabled by effective policies such as improved energy efficiency standards for buildings, appliances, vehicles, and machines; product labeling; and taxes and subsidies. However, to achieve final energy demand reductions represented in the three GEA pathway groups, technological measures to improve efficiency need to be complemented by political, regulatory, and institutional measures to shift and limit energy services demand.

The final energy intensity of the global economy (measured in terms of megajoules of final energy consumed per 2005 US dollars of GDP at market exchange rates) is projected to decline over the course of the century regardless of the two pathways shown in this chapter. Specifically, it declines at an average annual rate of 1.5 percent and 0.8 percent between 2010 and 2100 in the illustrative GEA-Mix pathway and the GEA counterfactual pathway, respectively (compared with 1.2 percent in the period between the early 1970s and now). Such large-scale improvements in the final energy intensity of the global economy require a portfolio of measures that stimulate the adoption of highly energy efficient end-use technologies, changes in the structure of the economy, and changes in energy services demand through lifestyle and behavioral shifts. Energy intensity improvements vary significantly at the regional level: developing regions are projected to experience more rapid energy intensity improvements than today's industrialized regions.

Figures 7.1a–d show the development of final energy demand by sector for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. Figure 7.1a shows that expected continuous economic growth in the world more than offsets improvements in the final energy intensity of the global economy in the two pathways, leading to an overall continuous increase in global final energy demand over the course of the century. It should, however, be noted that the growth rate of final energy demand can be suppressed in the illustrative GEA-Mix pathway; for example, levels of final energy demand are stabilized in Centrally Planned Asia (see Figure 7.1b). Globally, final energy demand increases by a factor of 3.4 and 1.8 between 2010 and 2100 in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively.

In the two pathways, the industrial sector remains the largest consumer of final energy in the world and in the three developing Asian regions until 2100 (except for 2010 in South Asia), consuming approximately half of total final energy consumption from 2030 at the latest in the world and in the three developing Asian regions. This implies that energy efficiency improvements in the industrial sector have significant importance for reducing total final energy demand. In the illustrative GEA-Mix pathway, a number of different measures are taken to reduce final energy demand in the industrial sector. These include: (1) the adoption of best available technologies for industrial processes, (2) the retrofit of existing plants, (3) the optimization of industrial systems designs, and (4) further electrification.

Globally, the final energy demand reduction rate in the illustrative GEA-Mix pathway compared with the GEA counterfactual pathway is highest in the transport sector over the period 2010–2100, which is estimated at 48.4 percent in 2050 and 53.5 percent in 2100. This trend



Figures 7.1 (a–d) Final energy demand by sector in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways

mostly holds for each of the three developing Asian regions, despite increasing reliance on individual mobility provided by cars in these regions. Such a large reduction in final energy demand in the transport sector in the illustrative GEA-Mix pathway results not only from efficiency improvements in the vehicle fleet but also from reduction in transport activity demand (expressed in passenger-kilometers (pkm) per year or tonne-kilometers (tkm) per year) and modal shift towards rail and bus with low energy intensity (expressed in megajoules of final energy consumed per pkm or tkm).

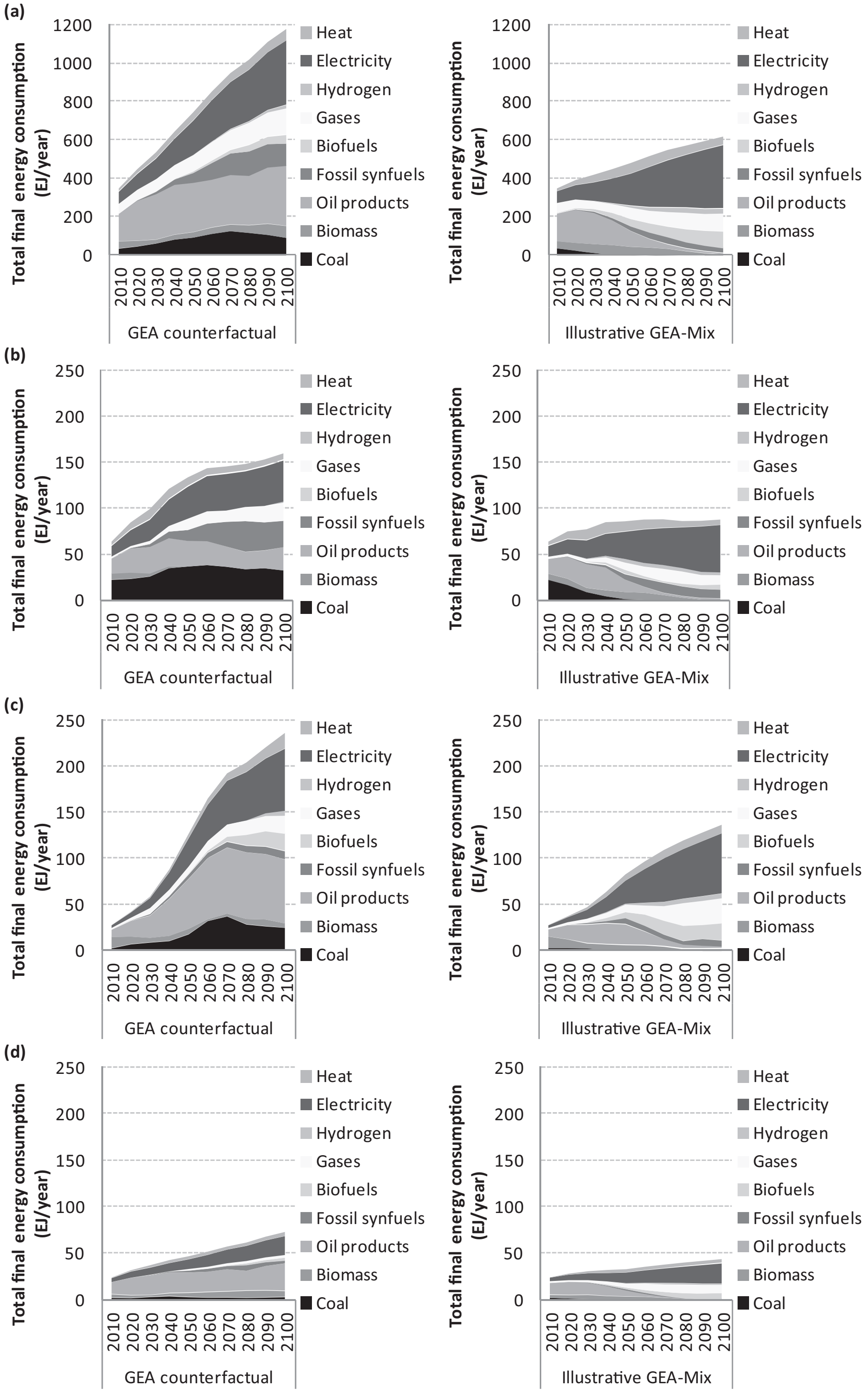
By contrast, in most regions and time points, the final energy demand reduction rate in the illustrative GEA-Mix pathway compared with the GEA counterfactual pathway is lowest in the residential and commercial sector over the period 2010–2100, although the potential efficiency improvements from buildings in terms of energy use avoided are estimated to be among the highest across all energy end-use sectors. In the illustrative GEA-Mix pathway, the potential for energy efficiency improvements for space heating and cooling is tapped, for example, by promoting thermal insulation as well as the retrofit of existing buildings. Also, the increasing penetration of air- or ground-source heat pumps driven by electricity contributes to efficiency improvements in the use of energy for this purpose.

Figures 7.2a–d show the development of final energy consumption by fuel for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. In Figures 7.2a–d and 7.3a–c, gases include natural gas, biogas, and synthetic natural gas, while heat includes district heating/cooling and solar thermal heat.

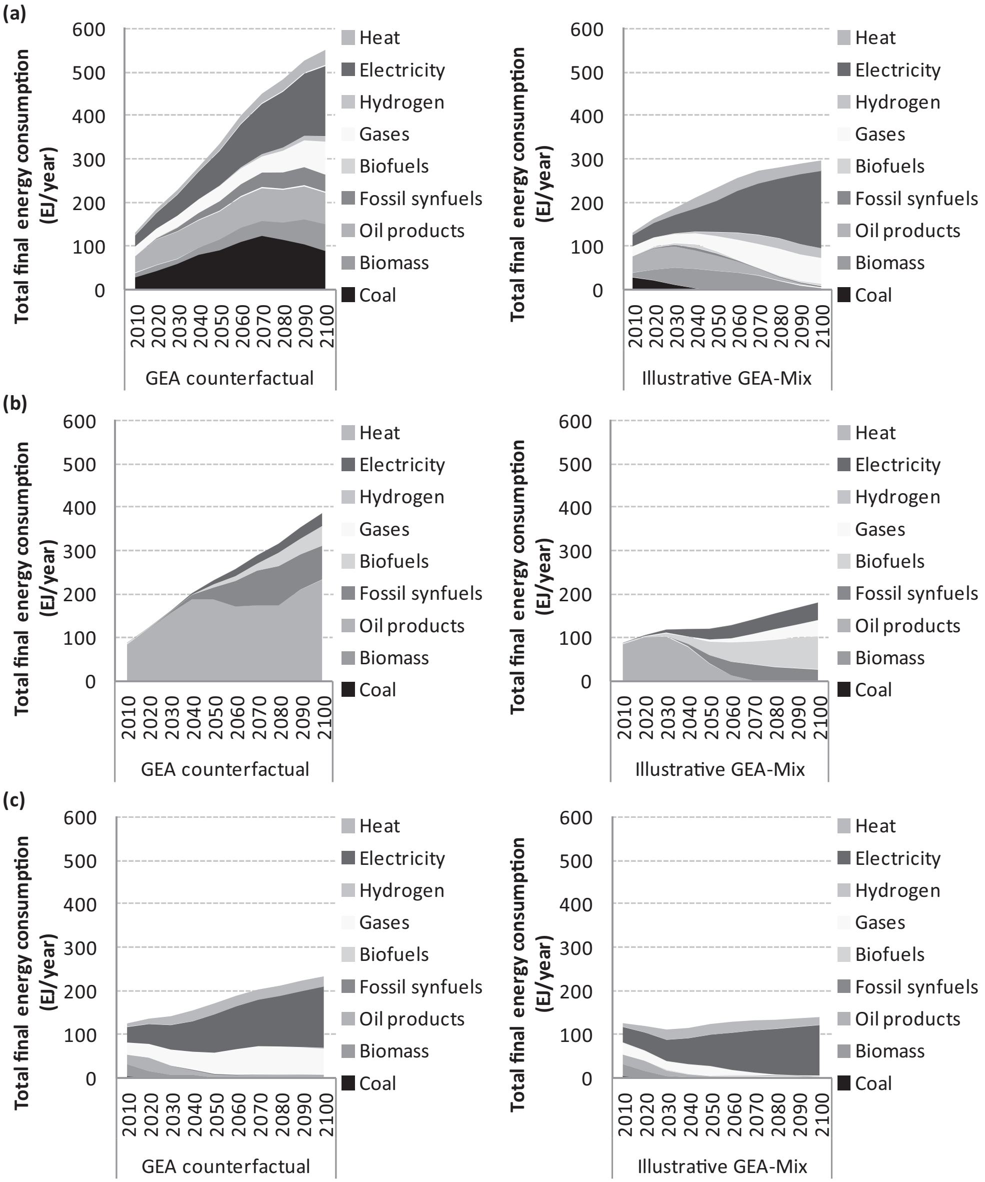
Similar patterns are observed for the global and regional evolution of the final energy mix in the illustrative GEA-Mix pathway. That is, the final energy mix in this pathway changes considerably over the course of the century, as the trend toward more flexible, more convenient, and cleaner energy carriers, such as electricity and gaseous fuels, grows significantly. By contrast, the structure of the final energy mix in the GEA counterfactual pathway would remain almost unchanged in the world and in the three developing Asian regions until 2100, except for the increasing share of electricity and fossil synfuels (which would compensate for the scarcity of the oil resource base). In this pathway, fossil-based energy carriers would continue to account for a significant share of final energy consumption in the world and in the three developing Asian regions.

There are three major characteristics of the structure of the final energy mix in the world and in the three developing Asian regions in the illustrative GEA-Mix pathway. First, oil products, today's prevailing fuels, as well as solid energy carriers (i.e., coal and biomass) are gradually phased out of the final energy market. The use of traditional biomass in the residential and commercial sector is phased out much earlier by 2030 due to improved energy access in developing regions. The share of solid energy carriers shown in Figures 7.2a–d after 2050 is predominantly modern biomass used as a substitute for coal in industrial processes. Second, electricity increases its share dramatically, accounting for 54.2 percent of global final energy consumption in 2100. Third, other grid-delivered or on-site-generated energy carriers (such as natural gas and hydrogen) and biofuels increase their contribution in absolute energy terms. Hydrogen plays a marginal role and is used only for industrial applications.

Figures 7.3a–c show the development of global final energy consumption by fuel for each energy end-use sector in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. Globally, electricity, natural gas, modern biomass, and hydrogen are the fuels of choice in the industrial sector in the illustrative GEA-Mix pathway, resulting in a reduction in direct CO_2 emissions in this sector. In particular, electricity and natural gas combined account for an increasing and ultimately dominant share of final energy consumption in the industrial



Figures 7.2 (a–d) Final energy consumption by fuel in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways



Figures 7.3 (a–c) Global final energy consumption by fuel in the industrial sector (a) in the transport sector (b) and in the residential and commercial sector (c) in the GEA counterfactual and illustrative GEA-Mix pathways

sector in this pathway. Hydrogen is used in direct reduction processes as a substitute for coal. Although not shown here, these trends also hold for each of the three developing Asian regions.

The transport sector would be dominated by oil products with a smaller contribution from other liquid fuels and electricity until 2100 in the GEA counterfactual pathway. However, the dominance of oil products in the transport sector lasts only for the short term in the illustrative GEA-Mix pathway. In this pathway, biofuels, electricity, and gases (mainly natural gas) replace oil use in the transport sector and contribute to decarbonizing the transport sector and diversifying its final energy mix over the medium-to-long term. Hydrogen is not introduced at all in the transport sector mainly because of technical hurdles for hydrogen fuel cell vehicles, their high costs, and extensive requirements for costly hydrogen supply infrastructure. These trends also hold for each of the three developing Asian regions.

Although the limited potential of sustainable bioenergy places an upper limit on the use of biofuels in the transport sector, biofuels account for an increasing share of total final energy consumption in the transport sector and ultimately become the largest source of the fuel supply for the transport sector in the world and in the developing Asian regions except Centrally Planned Asia in the illustrative GEA-Mix pathway. In Centrally Planned Asia in this pathway, fossil synfuels have an increasing share of the final energy mix and play the same role as biofuels do in the world and in the above two developing Asian regions (i.e., South Asia and Other Pacific Asia). Fossil synfuels production is combined with CO_2 capture and storage (CCS) to reduce CO_2 emissions caused by their production.

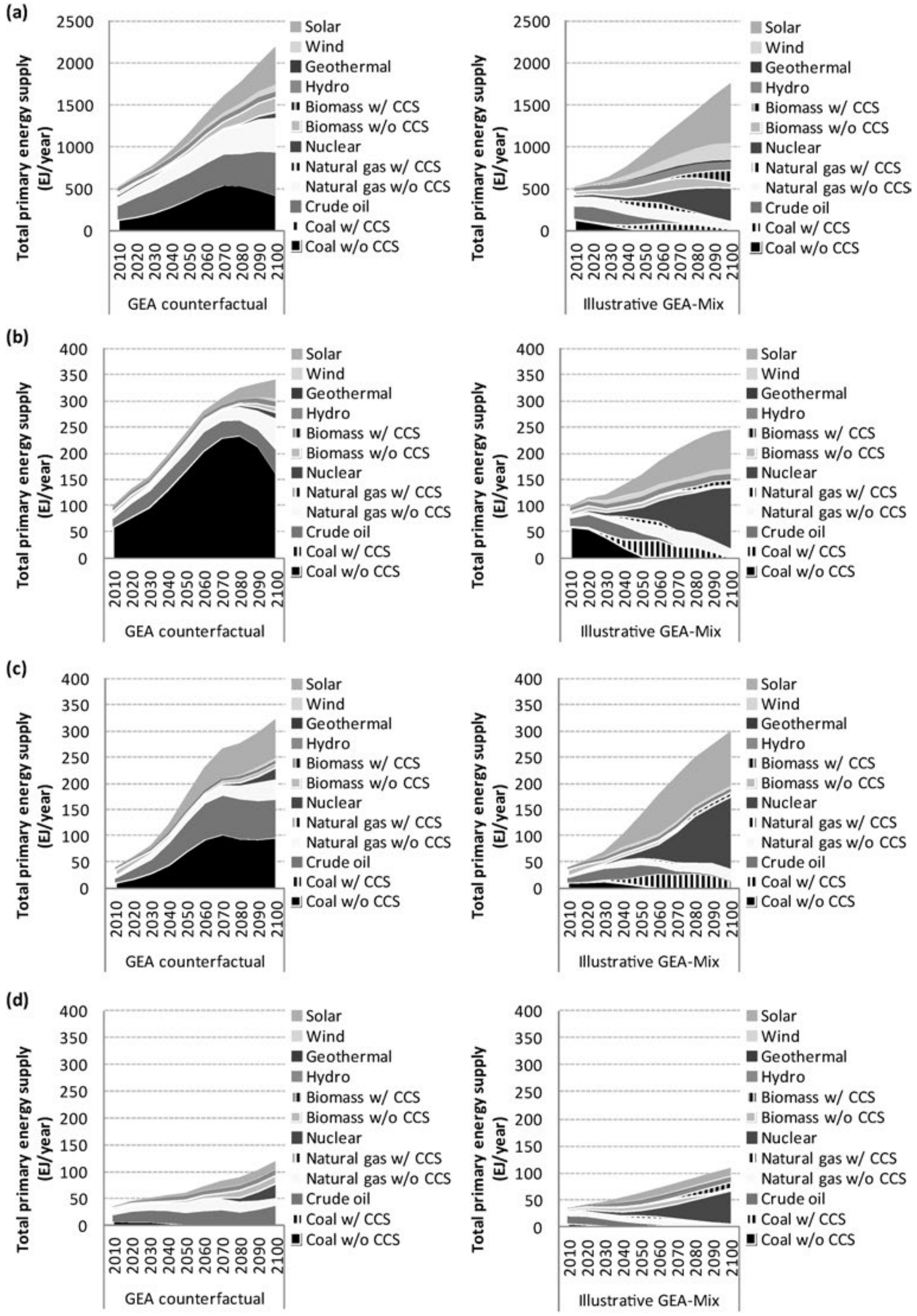
As regards oil consumption, the transport sector continues to be the largest oil consumer of all energy end-use sectors in the world and in the three developing Asian regions until around the middle of the century in the two pathways. However, in the illustrative GEA-Mix pathway, the industrial sector overtakes the transport sector as the largest oil consumer thereafter. At the global level, the share of the transport sector in global oil consumption in this pathway decreases from 58.5 percent in 2010 to 48.3 percent in 2050 and then to zero from 2080 onwards. It is worth noting that the transport sector ultimately becomes the smallest oil consumer of all energy end-use sectors in the world and in the three developing Asian regions in the illustrative GEA-Mix pathway.

As Figure 7.3c illustrates, the final energy mix in the residential and commercial sector is very similar in the two pathways: electricity, gases, and heat dominate final energy consumption in this sector. This means that even in the GEA counterfactual pathway, the trend toward the decarbonization of the residential and commercial sector would progress over time. The only clear difference between the two pathways is that electricity increases its share at the expense of gases in the illustrative GEA-Mix pathway, whereas gases would continue to be one of the central sources of the fuel supply for this sector until 2100 in the GEA counterfactual pathway. As a result, direct CO_2 emissions in the residential and commercial sector are further reduced in the former pathway. It is also important to note that the electrification rate is highest in the residential and commercial sector of all energy end-use sectors. Although not shown here, solar thermal heat accounts for a larger share of the final energy mix in the residential and commercial sector in Centrally Planned Asia and Other Pacific Asia than in the world.

3.2 Supply-side energy system transformations

Figures 7.4a–d show the development of primary energy supply by energy source for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. Here, similar to Riahi et al. (2012), the substitution method is used to calculate primary energy by assuming a 35 percent efficiency for electricity generation from non-combustible sources and an 85 percent efficiency for heat production.[7] Note that secondary energy import is not taken into account in Figures 7.4a–d.

In the GEA counterfactual pathway without any transformational policies to meet the sustainability goals, the global energy system would continue its heavy reliance on fossil fuels: the contribution of fossil fuels to the global primary energy supply would more than double by 2050 (reaching about 900 EJ) and more than triple by 2100 (reaching about 1,300 EJ). By contrast, the primary energy supply mix in the illustrative GEA-Mix pathway is considerably different



Figures 7.4 (a–d) Primary energy supply by energy source in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways

from that of today and that in the GEA counterfactual pathway both globally and regionally. In this pathway, renewables (mainly solar, wind, and biomass) and nuclear gain share at the expense of fossil fuels, particularly coal and crude oil, and play an important role in the world and in the three developing Asian regions. Such a phase-out of coal and crude oil is not because of the scarcity of their resource bases but because of the limited carbon emissions budgets under the stringent climate stabilization target. It is interesting to note that even in the GEA counterfactual pathway, the share of renewables in the total primary energy supply in the world and in the three developing Asian regions would increase over time and become pronounced by the end of the century at the latest.

The primary energy structure in the two pathways is characterized by high levels of regional diversity, although this characteristic is less pronounced in the illustrative GEA-Mix pathway. For example, the options for decarbonizing primary energy supply vary by region depending mainly on regional differences in resource supply curves for each primary energy source and in the availability of low-carbon supply-side technological solutions such as nuclear and CCS. Specifically, nuclear, solar, coal with CCS, wind, and biomass with and without CCS are selected in Centrally Planned Asia; nuclear, solar, and coal with CCS are selected in South Asia; and nuclear and biomass with CCS are selected in Other Pacific Asia.

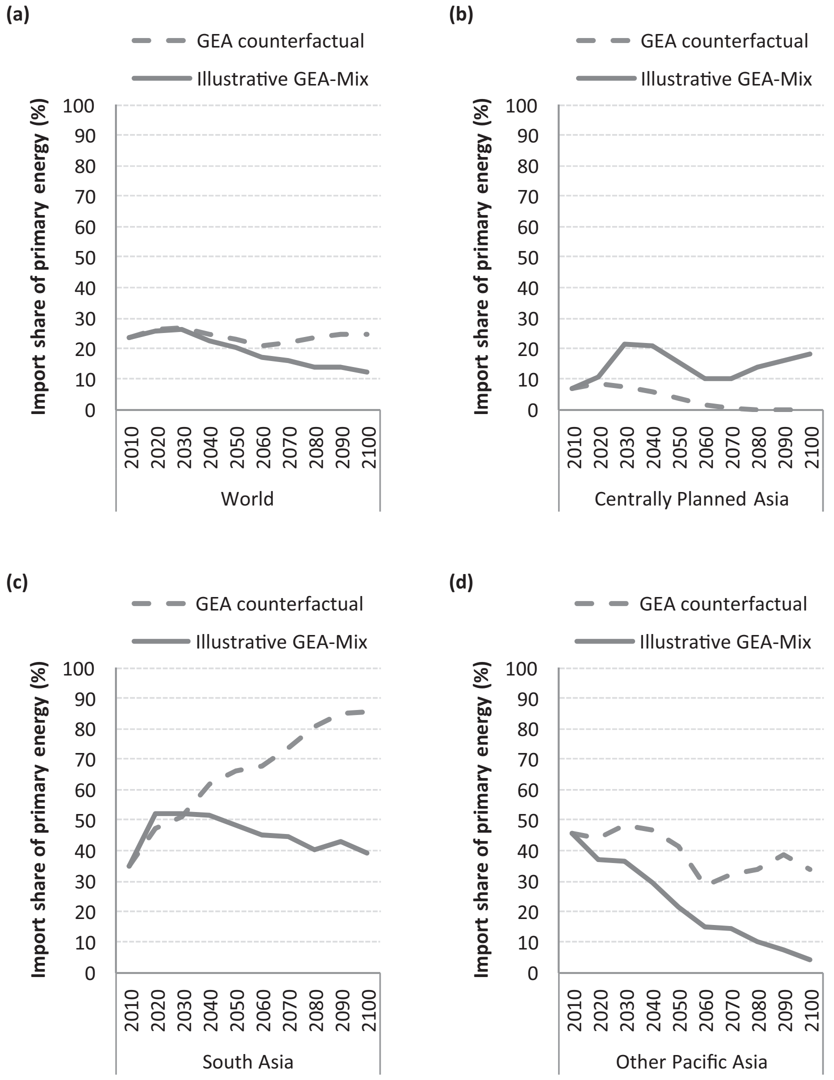
In the two pathways, the share of renewables in total primary energy supply is generally smaller in the three developing Asian regions than in the world. In particular, the global preference for wind and biomass is weak in the three developing Asian regions. This is primarily due to those regions' high population density and to potential land use and other conflicts that limit, for example, their potential for wind energy and/or sustainable bioenergy. Solar becomes by far the largest primary renewable energy source in Centrally Planned Asia and South Asia, whereas biomass, solar, and hydro are the main sources of primary renewable energy supply in Other Pacific Asia. In the illustrative GEA-Mix pathway, the exploitation rate (defined as the ratio of actual production to maximum potential production) is higher for modern biomass than for other renewables partly due to the higher tradability of liquid biofuels compared with electricity and heat. Such large-scale modern biomass production requires large amounts of land and water and thus has a possibility of leading to land scarcity, crop price increases, and biodiversity loss. This implies the need for additional policies to avoid these negative impacts and strict monitoring of biomass production and land use for this purpose.

In the two pathways, especially the illustrative GEA-Mix pathway, the deployment of coal and nuclear occurs intensively in the three developing Asian regions. In the illustrative GEA-Mix pathway, these regions account for 76.3 percent in 2050 and 77.3 percent in 2100 of global primary production of coal and account for 65.3 percent in 2050 and 80.9 percent in 2100 of global primary production of nuclear energy. For nuclear energy to account for such a large share of total primary energy supply in the developing Asian regions, important barriers to nuclear energy implementation, namely safety risks, proliferation risks, and waste management problems, must be addressed.

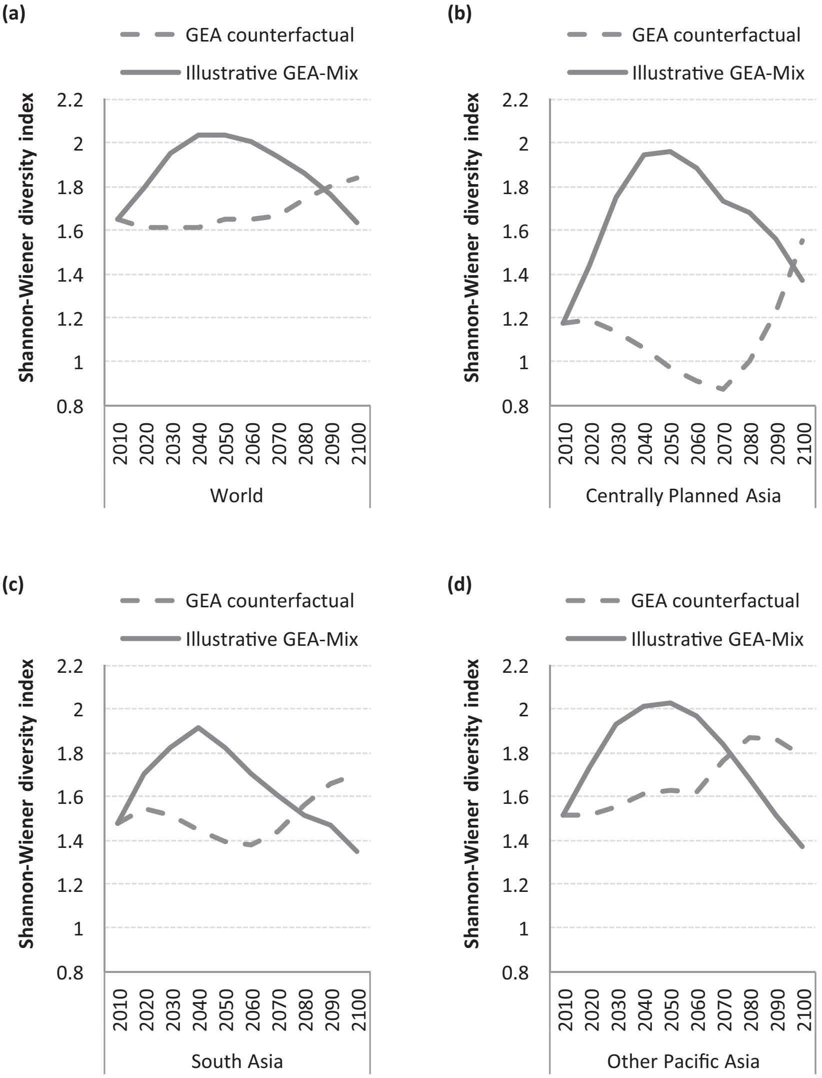
In the illustrative GEA-Mix pathway, the large-scale commercial deployment of CCS begins in 2030 (see also Figure 7.10). In this pathway, Centrally Planned Asia and South Asia are the regions with the largest and the second-largest cumulative CO_2 storage needs over the century of all the 11 world regions because of their large coal resource base and correspondingly high utilization of coal with CCS. The contribution of coal to the global primary energy supply in this pathway decreases until 2040, but then increases until 2060 and does not completely disappear until 2100 on the condition that CCS can be successfully deployed on a large scale. Furthermore, in this pathway, whereas the vast majority of CO_2 captured by 2050 comes from fossil fuels (i.e., coal and natural gas), biomass in combination with CCS, which enables negative CO_2

emissions, contributes visibly to the primary energy supply mix in the world and in the developing Asian regions except South Asia in the second half of the century and makes a large contribution to achieving the stringent climate stabilization target. For CCS to play such an important role in the developing Asian regions, the challenges associated with financing and technology transfer must be overcome.

Figures 7.5a–d show the development of the import share of primary energy supply for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. Also, to examine the diversity of primary



Figures 7.5 (a–d) The import share of primary energy supply in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways



Figures 7.6 (a–d) The Shannon-Wiener diversity index in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways

energy supply, Figures 7.6a–d show the development of the Shannon-Wiener diversity index (SWDI)[8] for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. The SWDI is calculated as follows:

$$SWDI = -\sum_i \left(p_i * \ln\left(p_i\right)\right) \tag{1}$$

where p_i is the share of primary energy i in total primary energy supply. An increase in the SWDI means an increase in the diversity of primary energy supply.

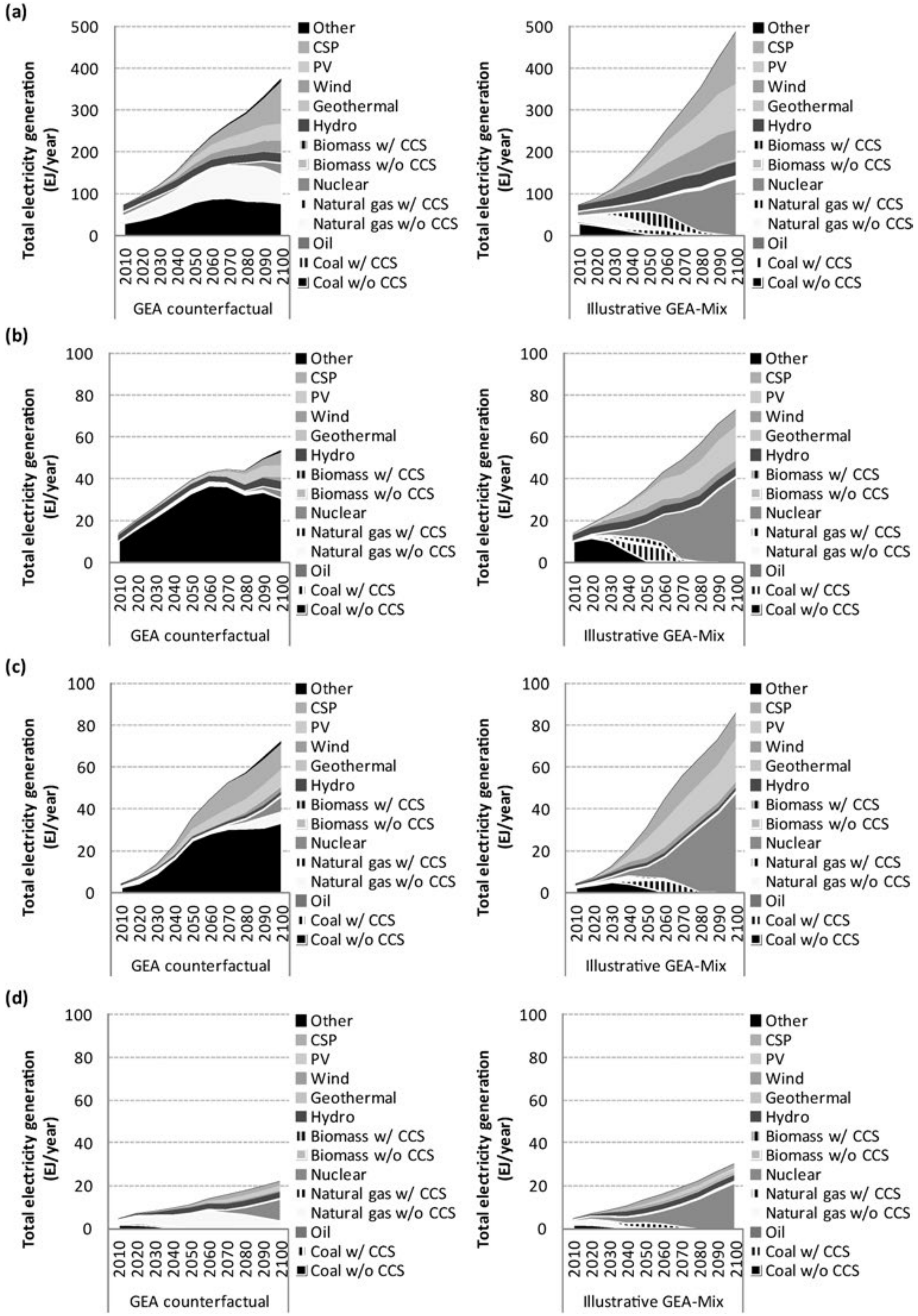
Figures 7.5a–d and 7.6a–d show that an improvement in energy supply security is, for the most part, achieved as a co-benefit of the decarbonization of the global energy system, taking into account that explicit constraints are not imposed on the diversity of primary energy supply (see Section 2.2). Except for Centrally Planned Asia, the import share of primary energy supply in the illustrative GEA-Mix pathway is generally lower than in the GEA counterfactual pathway. Furthermore, the SWDI (i.e., the diversity of primary energy supply) in the illustrative GEA-Mix pathway becomes much higher than in the GEA counterfactual pathway around the middle of the century in the world and in the three developing Asian regions. However, the results show that there is a trend reversal in which the SWDI in the illustrative GEA-Mix pathway becomes lower than in the GEA counterfactual pathway toward the end of the century in all the 11 world regions except the Middle East and North Africa. This suggests that not only climate change mitigation policies, but also dedicated policies aimed at improving energy supply security are needed to completely meet the four sustainability goals adopted for the GEA analysis.

As shown in Figures 7.2a–d, electricity becomes the most important final energy carrier in the world and in the three developing Asian regions in the illustrative GEA-Mix pathway. Hence, the focus is now placed on examining the optimal mix of electricity generation technologies. Figures 7.7a–d show the development of electricity generation by technology for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively (PV is an abbreviation for photovoltaics and CSP is an abbreviation for concentrated solar power). It can be seen that electricity generation in the illustrative GEA-Mix pathway becomes higher than in the GEA counterfactual pathway from 2060 onwards in the world, Centrally Planned Asia, and South Asia and from 2030 onwards in Other Pacific Asia. This is mainly because of additional electricity use for CCS and the further electrification of the transport sector in the illustrative GEA-Mix pathway.

Except for the negligible contribution of oil and biomass to the electricity generation mix, the temporal and spatial trends of electricity generation are similar to those of the primary energy supply in the two pathways. In the GEA counterfactual pathway, the electricity generation sector would be dominated by fossil fuels without CCS (excluding oil), with a small but increasing contribution of renewables (mainly solar) and nuclear until 2100 in the world and in the three developing Asian regions. By contrast, in the illustrative GEA-Mix pathway, renewable electricity generation technologies (mainly solar, wind, and hydro), nuclear electricity generation technologies, and fossil-based electricity generation technologies with CCS play an important role, whereas conventional fossil-based electricity generation technologies without CCS are phased out of the electricity generation portfolio. As a result, almost full decarbonization of the electricity generation sector is achieved by the middle of the century in the world and in the three developing Asian regions.

In the illustrative GEA-Mix pathway, fossil fuels with CCS provide a transitional bridge for the electricity generation sector; their contribution increases until around the middle of the century and then declines. This is because electricity supply from fossil fuels with CCS causes non-negligible CO_2 emissions (the rate of CO_2 capture being estimated in the range of 85 percent to 95 percent (IEA and NEA, 2010)). Renewables and nuclear, on the other hand, play an increasing role in this pathway over time and ultimately dominate the electricity generation sector. The temporal trends of electricity generation described previously hold not only for the world as a whole but also for the three developing Asian regions, although the relative importance of each of these low-carbon electricity generation technologies varies by region for the reasons stated in the results for primary energy supply.

Globally and regionally, solar electricity generation technologies (both solar PV and CSP technologies) account for a large share of total electricity generation in the medium to long term



Figures 7.7 (a–d) Electricity generation by technology in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways

in the illustrative GEA-Mix pathway, whereas flexible electricity generation technologies (such as natural gas combined-cycle power plants and pumped-storage hydropower plants) play a marginal role. This suggests an increasing requirement for technical measures that enable reliable integration of large amounts of electricity from intermittent renewable energy sources into electricity grids. These include, but are not limited to, storage technologies (such as batteries, flywheels, super-capacitors, hydrogen production and storage systems, and super-conducting systems), demand-side management, methods to predict renewable energy supplies many hours ahead, and backup power plants.

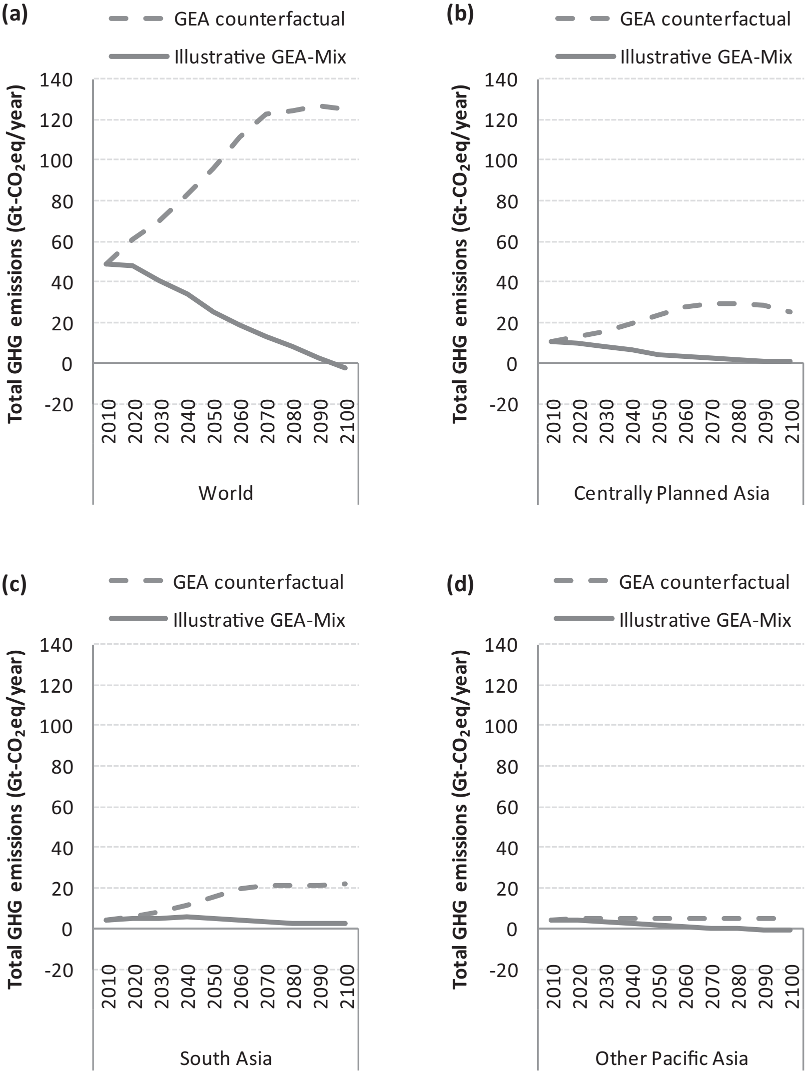
As noted in the results for primary energy supply in the illustrative GEA-Mix pathway, the majority of deployment of coal-fired and nuclear electricity generation technologies materializes in the three developing Asian regions. In the illustrative GEA-Mix pathway, the share of these base-load electricity generation technologies in total electricity generation increases from 45.4 percent in 2050 to 56.7 percent in 2100 in Centrally Planned Asia, from 36.5 percent in 2050 to 56.6 percent in 2100 in South Asia, and from 28.9 percent in 2050 to 72.7 percent in 2100 in Other Pacific Asia. In the light of such a large share of base-load electricity generation technologies and a trend toward an increasing difference between maximum and minimum daily electric demand in these regions, solar electricity generation technologies are expected to play a central role in meeting peak load demand.

In the two pathways, the role of biomass in the electricity generation mix is negligible in the world and in the three developing Asian regions. This result and the results of Figures 7.2a–d and 7.4a–d imply that it is cost-effective to preferentially use biomass to supply solid, liquid, and gaseous fuels. This is because conversion of biomass into these fuels is more energy efficient than conversion into electricity and because of the limited supply potential of sustainable bioenergy.

3.3 GHG emissions

Figures 7.8a–d show the development of total GHG emissions for the world and for each of the three developing Asian regions in the GEA counterfactual pathway and the illustrative GEA-Mix pathway, respectively. In the GEA counterfactual pathway, global total GHG emissions would increase monotonically until 2070 to reach 2.5 times larger than 2010 levels. After that time, they would increase only slightly until 2090 and decrease thereafter, reflecting the increasing share of renewables and nuclear in the global primary energy supply (see Figures 7.4a–d). According to Riahi et al. (2012), such a trend for global total GHG emissions might force the global mean temperature increase to reach 5 °C above pre-industrial levels in the long term.

By contrast, global total GHG emissions in the illustrative GEA-Mix pathway exhibit a continuously declining trend from 2010 onwards: they are reduced to 52.2 percent of 2010 levels in 2050 and reach negative levels in 2100 (–2.6 $GtCO_2$-eq), which can be achieved by large-scale deployment of bioenergy combined with CCS and enhancement of the terrestrial sink potential, such as afforestation and reforestation. This suggests the need for very ambitions short-term GHG mitigation policies and their increasing stringency over time under the stringent climate stabilization target. Total GHG emissions in Centrally Planned Asia in this pathway also follow a continuously declining trajectory, whereas those in South Asia and Other Pacific Asia continue to increase until 2040 and 2020, respectively, and decline thereafter. As a result, total GHG emissions in the developing Asian regions except South Asia reach very low to negative levels by 2100 (0.83 $GtCO_2$-eq in Centrally Planned Asia and –0.69 $GtCO_2$-eq in Other Pacific Asia). On the other hand, the level of GHG emissions reduction in this pathway is rather modest in South Asia: total GHG emissions in South Asia in this pathway are reduced to 2.2 $GtCO_2$-eq in 2100, which are 57.2 percent of 2010 levels.



Figures 7.8 (a–d) Total GHG emissions in the world (a) Centrally Planned Asia (b) South Asia (c) and Other Pacific Asia (d) in the GEA counterfactual and illustrative GEA-Mix pathways

To identify the most cost-effective pattern of spatially sharing the burden of a reduction in global total GHG emissions, Figure 7.9 shows the contribution of the 11 world regions to a reduction in cumulative global total GHG emissions over the period 2010–2100 in the illustrative GEA-Mix pathway compared with the GEA counterfactual pathway. The result shows that there is a large difference in regional contribution to a reduction in cumulative global total GHG emissions over this period. It can also be seen that the three developing Asian regions account for a very large share (43.5 percent) of a reduction in cumulative global total GHG emissions over this period, despite a considerable increase in energy services demand and other GHG-emitting activities in these regions. Centrally Planned Asia and South Asia are the largest and the second largest

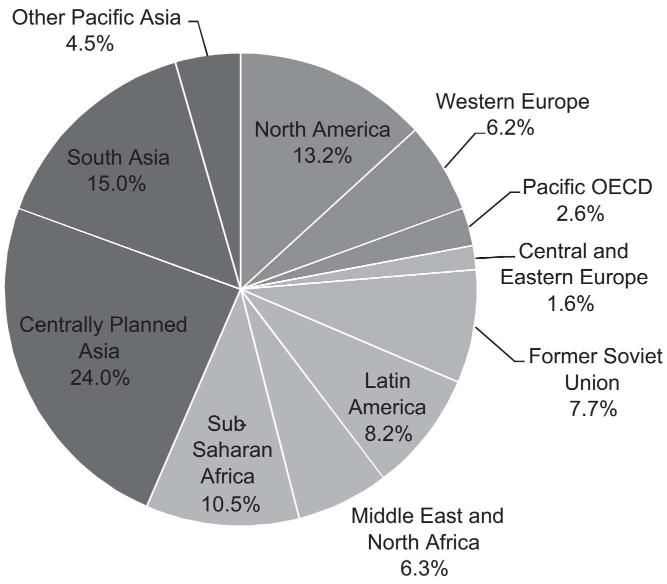


Figure 7.9 Regional breakdown of a reduction in cumulative global total GHG emissions over the period 2010–2100 in the illustrative GEA-Mix pathway compared with the GEA counterfactual pathway

contributors, accounting for 24.0 percent and 15.0 percent of a reduction in cumulative global total GHG emissions, respectively. This means that there is a large low-cost GHG mitigation potential in these regions.

3.4 Contribution of technology options to reducing global energy-related CO_2 emissions under the stringent climate stabilization target

The so-called Kaya identity (Kaya, 1989), which is expressed in equation (2), helps to identify technology options that can contribute to achieving a reduction in global energy-related CO_2 emissions without having a negative impact on economic growth.

$$C_n = \frac{C_n}{C_g} \times \frac{C_g}{PE} \times \frac{PE}{GDP} \times GDP \tag{2}$$

where C_n is the net global energy-related CO_2 emissions, C_g is the gross global energy-related CO_2 emissions, *PE* is the global primary energy consumption, and *GDP* is the global GDP.

The term C_n/C_g represents how widespread the deployment of CCS is, the term C_g/PE represents the carbon intensity of global primary energy consumption, and the term *PE/GDP* represents the primary energy intensity of the global economy. It can be drawn from equation (2) that the target of reducing net global energy-related CO_2 emissions without compromising economic growth requires a decrease in C_n/C_g, C_g/PE, and/or *PE/GDP* in equation (2). This means that the deployment of CCS, fuel switching to less carbon-intensive fuels, and energy intensity improvements leading to energy savings are three technology options for meeting this target.

The focus is now placed on examining the contribution of each of the three technology options to reducing net global energy-related CO_2 emissions under the four sustainability goals adopted for the GEA analysis. Net global energy-related CO_2 emissions also can be expressed as follows:

$$C_n = \frac{C_n}{C_g} \times \frac{C_g}{PE_f} \times \frac{PE_f}{PE} \times PE \tag{3}$$

where PE_f is the global primary fossil energy consumption.

Following the approach proposed by Akimoto et al. (2004), the contribution of each of the three technology options to reducing net global energy-related CO_2 emissions under the constraint that the global mean temperature increase should be limited to 2 °C above pre-industrial levels with a likelihood of more than 50 percent can be derived from equation (4).

$$\begin{aligned} C_n^B - C_n^S &= \left(C_g^B - CCS^B\right) - \left(C_g^S - CCS^S\right) \\ &= \left(CCS^S - CCS^B\right) + PE^S\left(\frac{C_g^B}{PE^B} - \frac{C_g^S}{PE^S}\right) + \frac{C_g^B}{PE^B}\left(PE^B - PE^S\right) \\ &= \left(CCS^S - CCS^B\right) + PE^S\frac{PE_f^S}{PE^S}\left(\frac{C_g^B}{PE_f^B} - \frac{C_g^S}{PE_f^S}\right) + PE^S\frac{C_g^B}{PE_f^B}\left(\frac{PE_f^B}{PE^B} - \frac{PE_f^S}{PE^S}\right) \\ &\quad + \frac{C_g^B}{PE^B}\left(PE^B - PE^S\right) \end{aligned} \tag{4}$$

where CCS is the amount of CO_2 sequestered, and the superscripts B and S denote the GEA counterfactual and illustrative GEA-Mix pathways, respectively.

The first term represents the contribution of CCS, the second term represents the contribution of fuel switching among fossil fuels, the third term represents the contribution of fuel switching to non-fossil fuels, and the fourth term represents the contribution of energy savings on both the demand and supply sides of the energy systems.

Figure 7.10 shows the contribution of each of the three technology options to reducing net global energy-related CO_2 emissions in the illustrative GEA-Mix pathway, which is calculated according to equation (4). It is readily apparent that all the three technology options need to be implemented to meet the stringent climate stabilization target. A large part of the reduction in global energy-related CO_2 emissions results from the decarbonization of energy supply, which is achieved through fuel switching and CCS. Especially fuel switching to non-fossil fuels (such as nuclear, solar, wind, and biomass) makes a significant contribution to reducing global energy-related CO_2 emissions. Energy savings on the demand and supply sides, which are achieved through energy efficiency improvements and price-induced energy demand reductions, also make a sizeable contribution.

Figure 7.10 shows that CCS is the smallest contributor to reducing global energy-related CO_2 emissions in the illustrative GEA-Mix pathway. The global amount of CO_2 captured for storage in this pathway increases until 2060 and then remains almost constant until 2100. It should, however, be noted that the contribution of CCS to reducing global energy-related CO_2 emissions varies significantly depending on levels of energy demand: under high demand levels as is assumed in the GEA-Supply pathways, cumulative global CO_2 storage by 2100 would be approximately 1.5 times larger than that in the illustrative GEA-Mix pathway. Cumulative global CO_2 storage by 2100 amounts to 98.3 $GtCO_2$ and 145.8 $GtCO_2$, respectively, in the illustrative GEA-Mix and illustrative GEA-Supply pathways. These values are much smaller than the best estimate of the global CO_2 storage capacity of approximately 2,000 $GtCO_2$ (Metz et al., 2005), implying that CO_2 storage capacity will not become a problem in the 21st century even under stringent climate stabilization targets.

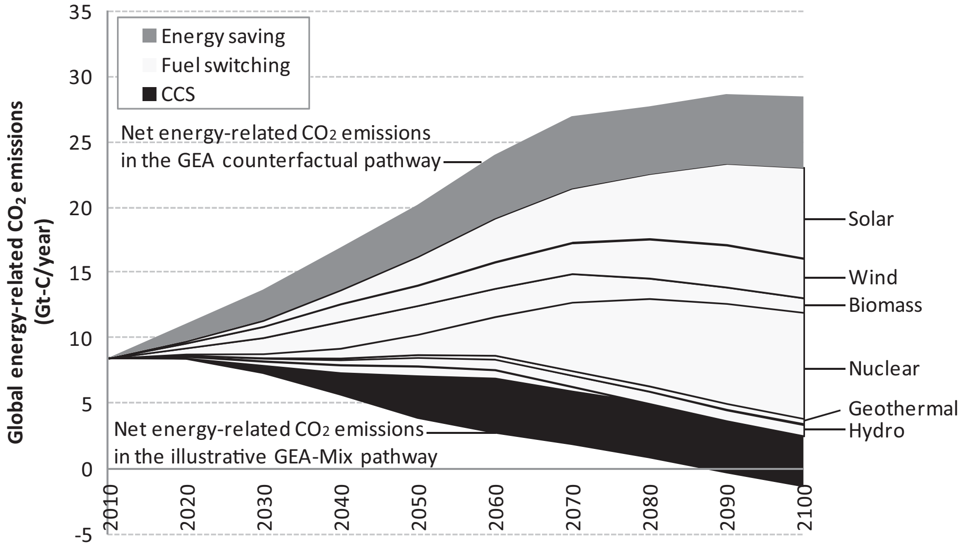


Figure 7.10 Contribution of technology options to reducing global energy-related CO_2 emissions in the illustrative GEA-Mix pathway

4. Conclusions

In this chapter, the illustrative GEA-Mix pathway presented by Riahi et al. (2012) has been shown and discussed in detail as an example of a sustainable energy pathway that can meet not only the ambitious goal of limiting the global mean temperature increase to 2 °C above pre-industrial levels with a likelihood of more than 50 percent but also that of improved energy access, reduced air pollution and improved human health, and energy security. It has been observed from the results of this pathway that early and profound transformations of the demand and supply sides of the energy systems are needed to simultaneously meet these stringent requirements in a cost-effective manner. Such transformations are technologically feasible but pose a formidable challenge for which strong policy interventions, considerable energy investments, and lifestyle and behavioral changes are absolutely essential.

From a short-term perspective, pledges currently in place or in the planning stages, mainly in industrialized countries, need to be tightened to meet the stringent climate stabilization target adopted for the GEA analysis. According to Rogelj et al. (2010) and UNEP (2010), even if all the present pledges made by various countries were to be executed successfully, global GHG emissions would amount to 47.9–53.6 $GtCO_2$-eq in 2020, which are larger than those in the illustrative GEA-Mix pathway. Furthermore, Riahi et al. (2012) estimate globally implemented CO_2 price levels that can keep global GHG emissions in 2020 between 2005 and 2010 levels to be in the range of US$15–45 per tonne of CO_2, compared with the current CO_2 permit price of just under US$ 5.2 per tonne of CO_2 that prevailed in the EU Emission Trading System[9] as of March 2013 (JPEC, 2013).

There seem to be two important issues not mentioned in this chapter. First, as pointed out by Riahi et al. (2012), special attention should be paid to discussing who must pay for such drastic GHG emissions reduction as those depicted by the illustrative GEA-Mix pathway. To address this equity issue, it is necessary to make a political compromise between industrialized countries (which are responsible for the bulk of the historical increase in atmospheric GHG concentrations) and developing countries (in which a large, low-cost GHG mitigation potential is estimated to exist). Second, in light of the difficulties in drastically cutting GHG emissions, not only mitigation strategies but also adaptation strategies need to be developed to avoid the catastrophic impacts of climate change. It should, however, be kept in mind that mitigation strategies are the first-order task because they are likely to have substantial co-benefits on local and regional environments, human health, and energy security and because there is a possibility that extended and prolonged reliance on adaptation would increase the moral dilemma (Riahi et al., 2012; Smith et al., 2012).

Notes

1 For definitions of regional classification, see Table 1.

2 GEA is an acronym for Global Energy Assessment, a publication by Johansson et al. (2012).

3 These two energy pathways also were developed using an integrated assessment modeling framework IMAGE. The GEA pathways quantified with the IMAGE model are not presented because this model excludes all solar energy technologies other than solar photovoltaics and thus significantly underestimates the potential contribution of solar energy.

4 In total, 41 pathways were developed within the three pathway groups having low, intermediate, and high estimates of energy demand evolution.

5 In Riahi et al. (2012), the GEA-Mix pathway assuming restrictions on the electrification of the transport sector in a conventional transportation world was selected as the illustrative case for the GEA-Mix pathway groups.

6 This likelihood refers to physical uncertainties associated with climate change, such as climate sensitivity, aerosol forcing, and ocean diffusivity, and does not refer to the likelihood of the implementation of political and/or technological measures to meet the goal in the future.

7 There are three main methods for calculating the primary energy equivalent of non-fossil energies (i.e., renewables and nuclear): the substitution method, the direct equivalent method, and the physical energy content method. For details, see, for example, Grubler et al. (2012).

8 For details, see, for example, Stirling (1998) and Jansen et al. (2004).

9 An exchange rate of 1 Euro per US$1.31 was used (MURC, 2013).

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