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Prospects for Renewable and Fossil-Based Electricity Generation in a Carbon-Constrained World

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ABSTRACT

In this paper, a regionally disaggregated global energy system model with a detailed treatment of the electricity supply sector is used to derive the cost-optimal choice of electricity generation technologies for each of 70 world regions over the period 2010-2050 under a constraint of halving global energy-related CO_2 emissions in 2050 compared to the 2000 level. It is first shown that the long-term global electricity generation mix under the CO_2 constraint becomes highly diversified, which includes coal, natural gas, nuclear, biomass, hydro, geothermal, onshore and offshore wind, solar photovoltaics (PV), and concentrated solar power (CSP). In this carbon-constrained world, 89.9% of the electricity generation from coal, natural gas, and biomass is combined with CO_2 capture and storage (CCS) in 2050. It is then shown that the long-term electricity generation mix under the CO_2 constraint varies significantly by world region. Fossil fuels with CCS enter the long-term electricity generation mix in all world regions. In contrast, there is a sharp regional difference in the renewable generation technology of choice in the long term. For example, the world regions suitable for PV plants include the US, Western Europe, Japan, Korea, and China, while those suitable for CSP plants include the Middle East, Africa, Australia, and western Asia. Offshore wind is deployed on a large scale in the UK, Ireland, Nordic countries, the southern part of Latin America, and Japan.

1. Introduction

Climate change is the most pressing and threatening issue facing human beings. However, the United Nations warned in a recent report [1] that international efforts to mitigate climate change are, at this stage, insufficient to meet the goal of keeping global warming to below 2.0 degrees Celsius above pre-industrial levels. In order to avoid dangerous climate change and to achieve sustainable development, a portfolio of rational greenhouse gas (GHG) mitigation actions must be identified and their implementation must be accelerated.

In response to such political needs, many research organizations have proposed desirable strategies for reducing CO_2 emissions from the energy sector under a global 2.0 degrees Celsius stabilization target. They have often indicated that the decarbonization of the electricity generation sector is an attractive CO_2 mitigation option in terms of CO_2 mitigation potential and cost-effectiveness (e.g., [2,3]). However, there are fewer studies available conducting a regionally detailed analysis on CO_2 mitigation strategies for the electricity generation sector, although they have insisted that desirable CO_2 mitigation strategies are very likely to vary by region depending on regional characteristics.

Thus, the purpose of this paper is to derive the cost-optimal choice of electricity generation technologies in regional detail over the period 2010-2050 under a constraint of halving global energy-related CO_2 emissions in 2050 compared to the 2000 level. Due to space limitations, the focus of this paper is confined to (1) the competitiveness of renewable and fossil-based electricity generation technologies under this constraint and (2) regional differences in technology choices in the electricity generation sector under this constraint. This is done by using the global energy system model REDGEM70 (an acronym for a REgionally Disaggregated Global Energy Model with 70 regions) [4,5], which treats the electricity supply sector in detail. For the model to be used for this purpose, it was updated to properly consider the variability of renewable electricity generation and flexibility measures needed to integrate variable renewables into a power grid.

2. Methodology

2.1. Overview of the REDGEM70 Model

REDGEM70 is a technology-rich, bottom-up global en-

ergy systems optimization model formulated as an intertemporal linear programming problem (see [5] for a schematic representation of the structure of the model). With a 5% discount rate, the model is designed to determine the cost-optimal energy strategy (e.g., the cost-optimal choice of technology options) from 2010 to 2050 at 10-year intervals for each of 70 world regions so that total discounted global energy system costs are minimized under constraints on the satisfaction of exogenously given energy end-use demands, the availability of primary energy resources, material and energy balances, the maximum market growth rates of new technologies, etc. In the model, price-induced energy demand reductions and energy efficiency improvements, fuel switching to less carbon-intensive fuels, and CO_2 capture and storage (CCS) in geologic formations are the three options for CO_2 emissions reduction.

Furthermore, in the current version of the model used in this study, there is also a constraint that global energy-related CO_2 emissions in 2050 are to be halved compared to the 2000 level. This constraint is imposed because the Intergovernmental Panel on Climate Change has concluded that a 50% to 80% reduction of global CO_2 emissions by 2050 compared to the 2000 level can limit the long-term global mean temperature rise to 2.0 degrees Celsius above pre-industrial levels [6]. The model has a full flexibility in where and how CO_2 emissions reduction is achieved to meet this constraint.

As described above, REDGEM70 uses 70 world regions. **Figure 1** shows how the 70 world regions are defined in the model. These 70 regions are categorized into "energy production and consumption regions" and "energy production regions". The whole world was first di-

vided into the 48 energy production and consumption regions to which future energy end-use demands are allocated. The 22 energy production regions, which are defined as geographical points, were then distinguished from the energy production and consumption regions to represent the geographical characteristics of the areas endowed with large amounts of fossil energy resources. While the 48 energy production and consumption regions cover the global final energy consumption, all the energy-related activities except final energy consumption are conducted in each of the two region types in the model. Such a detailed regional disaggregation enables the explicit consideration of regional characteristics in terms of energy resource supply, energy demands, geography, and climate.

Future trajectories for energy end-use demands were estimated as a function of those for socio-economic driving forces such as population and income in the intermediate B2 scenario developed by [7]. Allocation of the energy end-use demand estimates to the 48 energy production and consumption regions was done by using country- and state-level statistics/estimates (and projections if available) on population, income, geography, energy use by type, and transport activity by mode, and by taking into account the underlying storyline of the B2 scenario that regional diversity might be somewhat preserved throughout the 21st century.

Assumptions on the availability and extraction cost of fossil energy resources and uranium resources were derived from [8] and [9], respectively. For non-biomass renewable resources, electricity supply potentials and electricity generation costs by world region are exogenous inputs to the model, which were obtained from
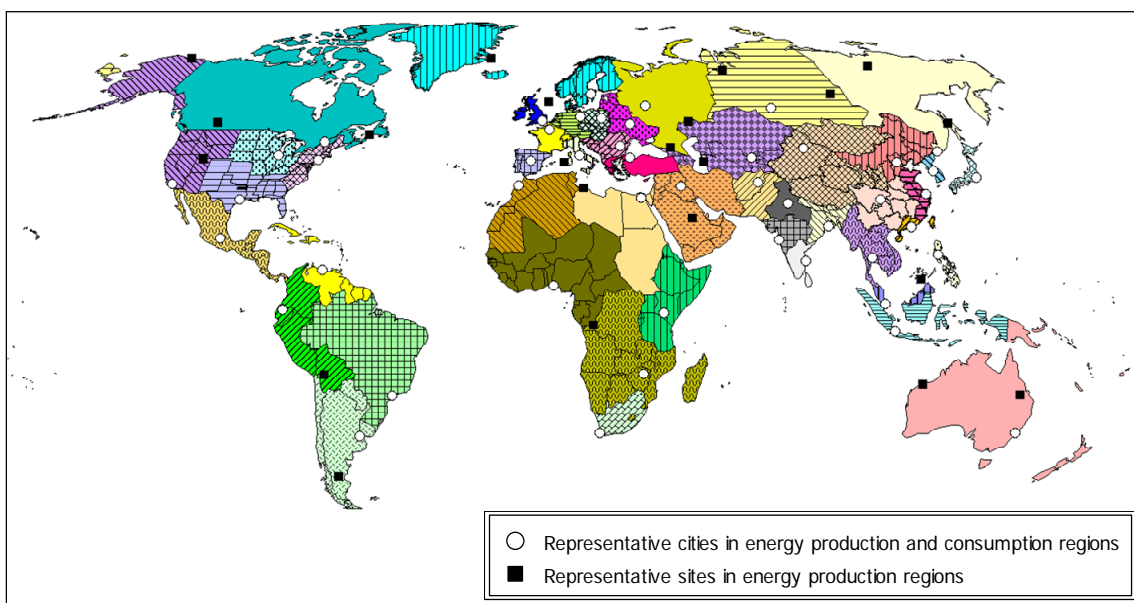
Figure 1. Regional disaggregation of REDGEM70.

[10,11]. For biomass resources, the model considers not only terrestrial biomass, but also waste biomass. The availability of these biomass resources and excess cropland that can be used for energy purposes without conflicting with other biomass uses such as food production was estimated for each region and each time point. They were estimated assuming that biomass is produced in a sustainable way so that biomass-derived energy carriers can be regarded as carbon neutral. Data for these biomass resources (e.g., resource availability, yields per hectare of land, and supply costs) are provided in [12]. These resource availability estimates were then allocated to the 70 model regions by using country-, state-, and site-level statistics/estimates.

2.2. Electricity Supply Sector Submodel

The electricity supply sector submodel of REDGEM70 was developed based on the ReEDS model [13]. In this submodel, time is subdivided within each 10-year time period: each year is divided into four seasons, each season is divided into three diurnal time-slices, and there is one superpeak time-slice. Given a set of input data and constraints, this submodel determines the cost-optimal choice of electricity generation technologies and electricity storage technologies for each region and each time point and determines their cost-optimal operation patterns for each region, each time-slice, and each time point.

This submodel explicitly takes into account the variability of wind and solar photovoltaics (PV) power, flexibility measures needed to integrate these variable renewables into a power grid (e.g., installing additional, flexible generation capacities and/or electricity storage technologies on the grid), and the costs associated with such measures. In contrast, it is assumed that concentrated solar power (CSP) plants have some form of heat storage to deliver power on demand and thus do not increase the operating reserve requirement [2]. This submodel also accounts for the cost of constructing adequate transmission capacity from renewable distributed generators to the nearest grid that must be built specifically to carry their generation.

Table 1 shows the input data for electricity generation technologies other than non-biomass renewables, while **Table 2** shows the input data for CO_2 capture technologies for power plants (which represent the bulk of the

Table 1. Data for electricity generation technologies other than non-biomass renewables[a].

Technologies	Capital cost[b] (US$2000/kW)	Conversion efficiency[b] (%, LHV basis)	Maximum capacity factor (%)	Technical lifetime (years)
Coal-fired steam cycle	1,500-1,170	43.0-52.0	85	40
Coal IGCC	1,680-1,300	46.0-54.0	85	40
Coal IGCC-SOFC	2,080-1,830	56.0-60.0	85	30
Oil-fired steam cycle	760-640	43.0-52.0	85	30
NGCC	630-530	57.0-63.0	85	30
NGCC-SOFC	1,260-1,060	66.0-70.0	85	30
Light-water nuclear reactor	2,350-2,100	34.0-37.0	85	40
Biomass-fired steam cycle				
using wood chips	1,880-1,460	24.9-34.0	85	30
using wood pellets	1,790-1,400	28.5-34.0	85	30
using grain residues	2,120-1,660	24.9-34.0	85	30
using sugarcane residues (a uniform mixture of bagasse and trash)	1,880-1,460	22.1-30.2 (electricity) 18.5 (heat)	85	30
using black liquor	4,420-3,440	12.4-13.0 (electricity) 61.0 (heat)	85	30
using municipal wastes	1,630-1,270	22.7-31.0	85	30
Biomass IGCC				
using wood chips	2,390-1,530	37.6-45.0	85	30
using wood pellets	2,300-1,470	39.8-47.1	85	30
using sugarcane residues (a uniform mixture of bagasse and trash)	2,780-1,780	32.4-37.9 (electricity) 18.5 (heat)	85	30
using black liquor	2,010-1,280	25.4-28.7 (electricity) 45.7 (heat)	85	30
Biogas-fueled gas engine for CHP applications	3,200-1,650	35.9-40.0 (electricity) 84.0 (total efficiency)	85	20

[a] Sources: [3,12,14-21]. LHV = lower heating value; IGCC = integrated gasification combined cycle; NGCC = natural gas combined cycle; CHP = combined heat and power; SOFC = solid oxide fuel cell. [b] These ranges denote the assumed evolution of the parameter values over the period 2010-2050. All cost numbers are based on North American manufacture and construction.

overall CCS costs). The input data for six types of stationary fuel cell technologies for CHP applications are not presented here because of space limitations. The actual model inputs for capital costs vary by word region by applying a region-specific plant location factor (see [22] for the location factor values). **Table 3** shows the global technical potential of six non-biomass renewable electricity technologies at different cost categories. These non-biomass renewable resource availability estimates were allocated to the 48 energy production and consumption regions based on data provided by [23]. Although not shown here, electricity generation technologies are also characterized by their load-following, quick-start, and operating/spinning reserve capabilities.

This submodel includes batteries and hydro-pumping as electricity storage technologies. The capital cost of batteries is assumed to decrease from 1,790 US$_{2000}/kW in 2010 to 1,290 US$_{2000}/kW in 2050, while their round trip efficiency is assumed to increase from 77% in 2010 to 82% in 2050 [13]. On the other hand, there is assumed to be potential for approximately 1,000 GW of pumped storage capacity worldwide, while the overall efficiency of pumped storage is assumed to be 80% [2]. The cost of

pumped storage systems is assumed to be 20% to 200% higher than that of equivalent unpumped hydropower systems depending on the cost category [2].

There are two important constraints imposed to integration of variable renewables into a power grid. First, the planning reserve margin constraints ensure that the sum of (1) the capacities of dispatchable generators and storage technologies and (2) the capacity value of variable renewable generators as represented by their effective load-carrying capability is larger than the annual peak load plus a reserve margin. The capacity value of each type of variable renewable electricity generation technology was calculated for each region and each time point using the approach proposed by [13,24]. Second, the operating reserve constraints ensure that the sum of the capacities of spinning reserves, quick-starts, and storage technologies is larger than the normal operating reserve requirement plus that imposed by variable renewables. The normal operating reserve requirement and the additional operating reserve requirement per unit capacity of variable renewable generators were calculated for each region, each time-slice, and each time point using the approach proposed by [13].

Table 2. Data for CO_2 capture technologies for new power plants[a].

Technologies	Incremental capital costs[b] (US$_{2000}/t-C/year)	Electric power required[b] (MWh/t-C)	CO_2 capture efficiency (%)
Post-combustion capture from coal steam cycle plants	240-210	1.077-0.861	90
Oxyfuel combustion capture from coal steam cycle plants	340-300	1.077-0.861	95
Pre-combustion capture from coal IGCC plants	130-110	0.861-0.646	90
Post-combustion capture from NGCC plants	370-330	1.535-1.343	90
Oxyfuel combustion capture from NGCC plants	470-420	1.814-1.633	95
Pre-combustion capture from biomass IGCC plants	280-250	0.702-0.526	90
Pre-combustion capture from black liquor IGCC plants	160-140	0.373-0.280	90

[a] Sources: [3,12,17,19,20]. [b] These ranges denote the assumed evolution of the parameter values over the period 2010-2050. All cost numbers are based on North American manufacture and construction. The incremental capital costs of CO_2 capture are assumed to be 60% higher for existing power plants than for new power plants, while the electric power consumption for CO_2 capture is assumed to be 32% higher for existing power plants than for new power plants [12].

Table 3. Technical potential of non-biomass renewable electricity supply in 2050 by cost category, in TWh/year[a].

Renewable electricity type	< 30 US$_{2000}/MWh	30 – 50 US$_{2000}/MWh	50 – 100 US$_{2000}/MWh	100 – 150 US$_{2000}/MWh	150 – 200 US$_{2000}/MWh
Hydroelectricity	3,151	6,673	4,065	0	0
Geothermal electricity	82	1,183	11,236	0	0
Onshore wind power[b]	1,254	23,891	70,562	9,570	0
Offshore wind power[b]	0	127	1,436	4,827	0
CSP[c]	0	42,842	180,753	52,377	0
Solar PV power[c]	54	450,314	14,601	5,032	0

[a] Sources: [10,11]. [b] The technical potential of onshore and offshore wind power is assumed to increase at an annual rate of 0.54% and 0.42%, respectively, until 2050, while the generation costs of onshore and offshore wind power are assumed to decrease at an annual rate of 1.04% and 1.03%, respectively, until 2030. [c] The technical potential of CSP and PV is assumed to increase at an annual rate of 0.48% and 1.14%, respectively, until 2050, while the generation costs of CSP and PV are assumed to decrease at an annual rate of 3.52% and 4.59%, respectively, until 2050.

3. Results and Discussion

3.1. Globally Aggregated Results for Electricity Generation

Before examining the simulation results on a regional basis, the focus is placed on the globally aggregated results. **Figures 2(a)** and **(b)** show the evolution of the global electricity generation for the business-as-usual (BaU) case without any CO_2 constraints and the case with the CO_2 constraint used here (called the CO_2 constraint case hereafter), respectively. The results indicate that among the four sectors (*i.e.*, industry, transport, buildings, and electricity generation), the electricity generation sector makes the largest contribution to reducing cumulative global CO_2 emissions over the period 2010-2050 from those in the BaU case, accounting for 64.7% of the total emissions reduction. This is the reason why there is a significant change in the choice of electricity generation technologies between the two cases. Renewables, CCS, and nuclear are the three largest contributors to CO_2 emissions reduction from the electricity generation sector in the CO_2 constraint case.

In the CO_2 constraint case, renewables account for a considerable share of the global electricity generation: the share of biomass, hydro, geothermal, onshore wind, offshore wind, solar PV, and solar CSP in the global electricity generation in 2050 is 5.1%, 15.0%, 2.5%, 10.3%, 2.0%, 6.2%, and 6.2%, respectively. In total, the share of renewables in the global electricity generation in the CO_2 constraint case increases from 20.6% in 2010 to 47.3% in 2050, while that in the BaU case decreases from 20.6% in 2010 to 20.3% in 2050.

On condition that the resulting CO_2 is properly captured and sequestered, fossil fuels remain an important source of the global electricity generation throughout the time horizon even under the stringent CO_2 emissions reduction constraint. In the CO_2 constraint case, the share of coal and natural gas in the global electricity generation in 2050 is 10.2% and 18.6%, respectively. The increasing deployment of CCS allows for the continued reliance on fossil fuels in the electricity generation sector in the CO_2 constraint case: the global penetration rate of CCS in fossil-based electricity generation technologies increases to 75.5% in 2050. Furthermore, clean coal technologies gain increasing importance in this CO_2-constrained world: the share of coal IGCC plants in the total global coal-based electricity generation increases to 23.5% in 2030 and to 90.4% in 2050 in the CO_2 constraint case. This is because coal IGCC plants are estimated to become more economical than coal-fired steam cycle plants if CCS becomes necessary [25].

3.2. Identifying World Regions where Each Technology Is Economically Attractive

In this section, a regionally detailed analysis is carried out to identify world regions where each electricity generation technology is economically attractive in the CO_2 constraint case. This is done to better understand regional differences in technology choices in the electricity generation sector in this case, which are examined in Section 3.3. **Figures 3(a)** and (**b**) show the cost-optimal technology choices in the electricity generation sector in the CO_2 constraint case by world region for 2030 and 2050, respectively.
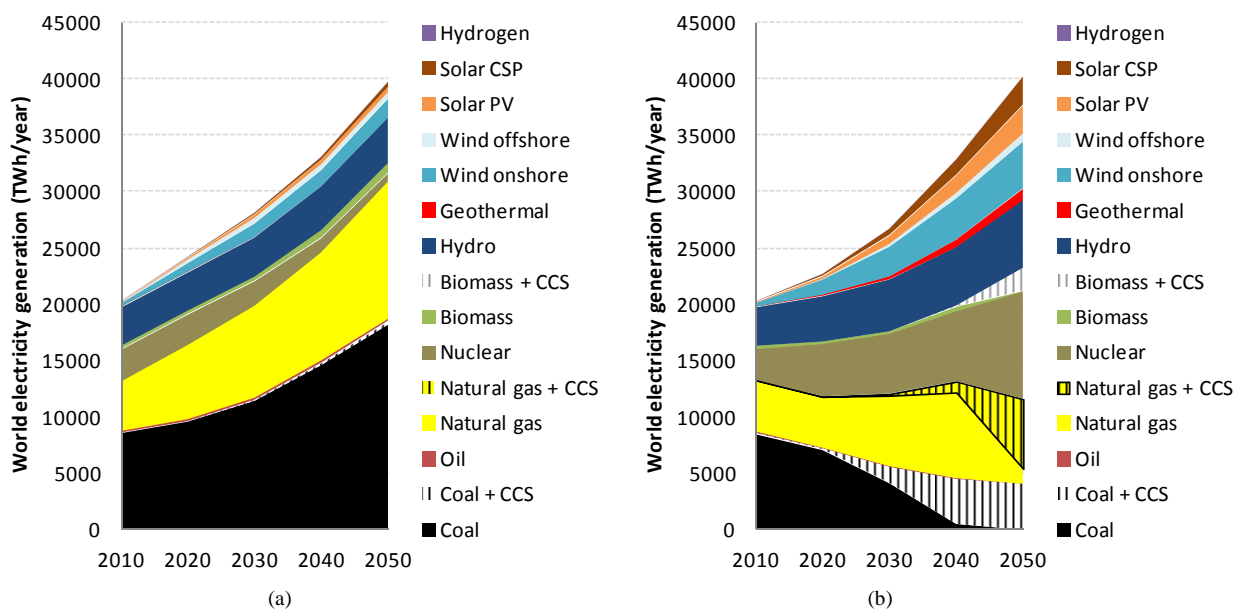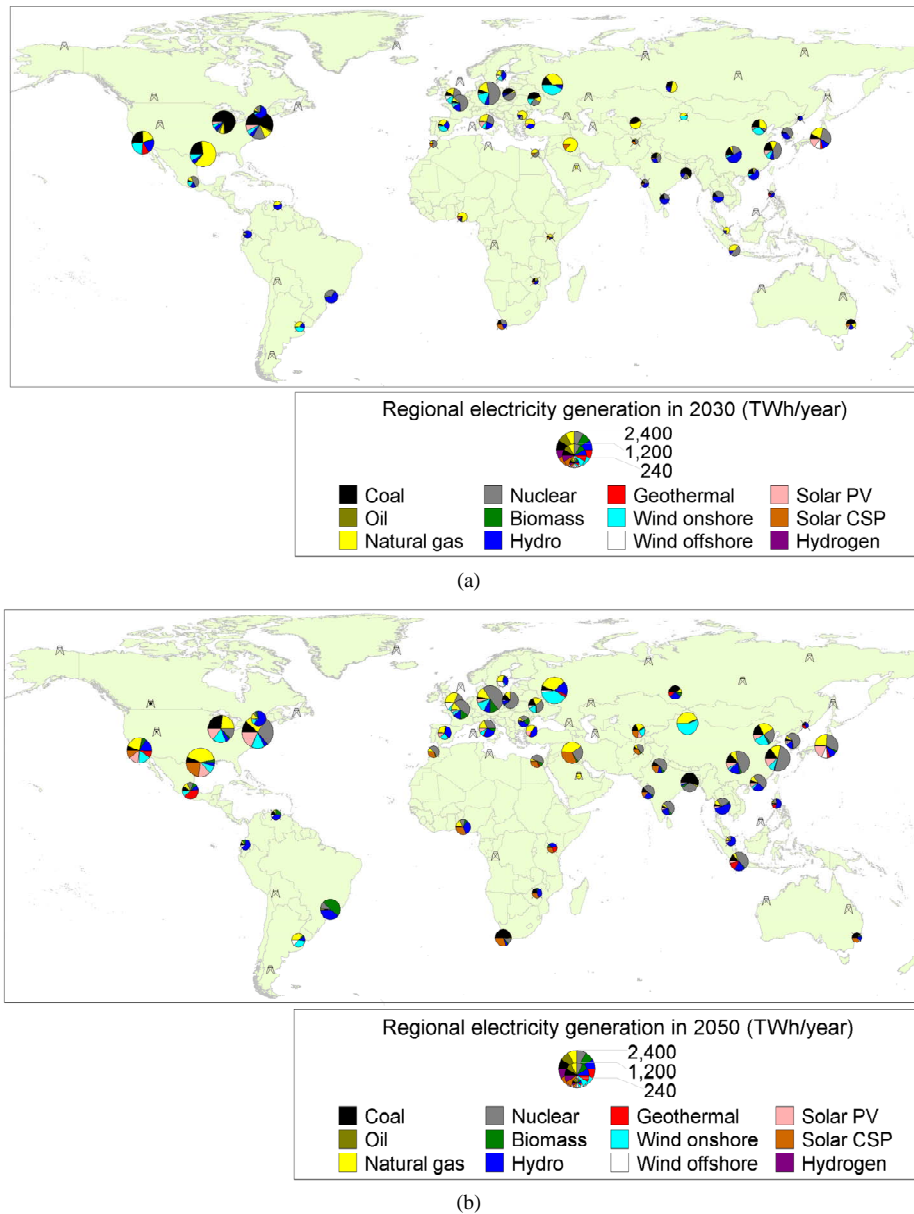

Figure 2. Global electricity generation in the BaU case (a) and the CO_2 constraint case (b).

Figure 3. Cost-optimal technology choices in the electricity generation sector in the CO_2 constraint case by world region in 2030 (a) and 2050 (b)[a].([a] Towers indicate representative sites in energy production regions, while crosses indicate representative cities in energy production and consumption regions.)

Fossil fuels retain their position as an important source of electricity generation in many world regions until 2050. Coal-based electricity generation technologies continue to be important until 2050 in regions such as India, the southern part of Africa, the Former Soviet Union, Oceania, the US, China (excluding western China), Eastern Europe, and Indonesia. Although not explicitly shown here, China, western Asia (mainly India), and the southern part of Africa take the lead in the deployment of coal IGCC plants. On the other hand, natural gas-based electricity generation technologies continue to be important until 2050 in regions such as the Middle East, China, the US, Europe, the southern part of Latin America, the Former Soviet Union, Japan, and West Africa. Coal-rich countries such as the US, India, China, Russia, and Australia take the lead in the deployment of CCS from electricity generation.

Hydro, onshore wind, and solar PV constitute one of the pillars of the long-term generation system in many parts of the world. In the case of hydro, it accounts for a large share of electricity generation in regions such as southeastern Asia, Canada, Latin America, Russia, Europe, India, inland central and southern China, tropical central Africa, the US, Korea, Oceania, and Japan. In the

case of onshore wind, it penetrates into the generation system in regions such as China, the southern part of Latin America, Western Europe, the Former Soviet Union, and North America. In the case of solar PV, it penetrates into the generation system in regions such as Japan, the US, China (excluding western China), Western Europe, Korea, parts of the Former Soviet Union, and southeastern Asia. This result is comparable to that of the International Energy Agency [2], which projected that solar PV would grow very significantly in solar-rich industrialized countries (particularly in the US) and China. In regions where onshore wind and/or solar PV are deployed, natural gas-based electricity plants and/or flexible hydroelectricity plants play a major role as a backup for these variable renewables.

In contrast, biomass-based electricity generation technologies (mainly biomass IGCC plants), geothermal electricity generation technologies, and offshore wind electricity generation technologies participate visibly in the electricity generation mix in a limited number of world regions in the long term. In 2050, biomass (most of which is combined with CCS) enters the electricity generation mix in biomass-rich regions such as Latin America and Europe. In the case of geothermal, it enters the long-term electricity generation mix in countries around the "Ring of Fire" (e.g., Indonesia, the Philippines, Central America, and the western coast of the US), rift zones (e.g., East Africa), and Russia. In the case of offshore wind, it enters the long-term electricity generation mix in Nordic countries, Latin America, the UK and Ireland, Japan, and Korea.

Solar CSP has a large share of electricity generation in the widespread Sunbelt regions, which include the Middle East, Africa, Australia, the southern US, and western Asia. In these regions with high direct solar radiation (excluding the southern US), solar PV is excluded from the electricity generation mix. This result is plausible because CSP electricity is estimated to be cheaper than solar PV electricity in the Sunbelt regions [2] and because flexibility measures need to be taken to integrate variable solar PV electricity into a power grid, which worsen its overall economics.

3.3. Regional Differences in Technology Choices in the Electricity Generation Sector

Taking into account the findings of Section 3.2, regional differences in long-term technology choices in the electricity generation sector in the CO_2 constraint case can be summarized as follows:

The long-term generation system in the US is characterized by diversified sources of electricity generation such as coal, natural gas, hydro, onshore wind, and solar PV. In addition, solar CSP plays an important role in the long-term generation system in the southern US, while

geothermal is deployed on a large scale in the long-term generation system in the western coast of the US. On the other hand, the Canada's generation system continues to be dominated by hydroelectricity. The Central America's long-term generation system is highly diversified and depends largely on geothermal electricity, while onshore and offshore wind play an important role in the generation system in the southern part of Latin America. The long-term generation system in other parts of Latin America is characterized by a large dependence on hydro and biomass and a small dependence on fossil fuels.

A distinctive feature of the long-term generation system in Western Europe and the southern part of Eastern Europe is that its components include hydroelectricity plants, onshore wind electricity plants (except in Turkey, Greece, Cyprus, and Eastern European countries), biomass-based electricity plants, and solar PV electricity plants (except in the UK, Ireland, and Nordic countries) and that it depends much less on coal-based electricity plants. Offshore wind is a significant part of the long-term generation system in the UK, Ireland, and Nordic countries. The Former Soviet Union's long-term generation system varies significantly by region. Coal, hydro, and geothermal are common sources of electricity generation in Russia in the long term, while onshore and offshore wind are deployed on a large scale in the long-term generation system in the western part of the Former Soviet Union.

Natural gas continues to dominate the Middle East's generation system. Also, the long-term generation system in the Middle East and Africa is characterized by a large dependence on solar CSP. Coal and hydro play marginal roles in the generation system in the Middle East and North Africa, while natural gas plays an important role only in the West Africa's generation system among Sub-Saharan Africa. Geothermal is deployed on a large scale in the East Africa's long-term generation system, while coal with CCS has a large share of the long-term generation system in the southern part of Africa.

The China's long-term generation system can be classified into three types. First, onshore wind and solar PV participate visibly in the generation system in northern and eastern China, but hydro has a very small participation in it. Second, the generation system in inland central and southern China is highly diversified, in which coal, natural gas, nuclear, hydro, onshore wind, and solar PV have a visible participation. Third, the western China's generation system is dominated by natural gas and onshore wind.

The western Asia's generation system is characterized by a small dependence on natural gas and wind (except in the northern part of western Asia). Not solar CSP but solar PV participates in the long-term generation system in eastern and southern India with the eastern India's

generation system relying heavily on coal with CCS. In contrast, solar CSP plays an important role in the long-term generation system in other parts of western Asia. Solar CSP and solar PV co-exist in the long-term generation system in the northern part of western Asia.

The southeastern Asia's long-term generation system is characterized by a large dependence on hydro, participation of solar PV, and absence of wind. Geothermal is deployed on a large scale in the long-term generation system in Indonesia and the Philippines. There are similarities in the long-term generation system in Japan and Korea, that is, these systems consist mainly of natural gas, nuclear, hydro, offshore wind, and solar PV. In addition, geothermal constitutes one of the pillars of the Japan's long-term generation system. On the other hand, coal with CCS, hydro, and solar CSP are the major components of the Oceania's long-term generation system.

4. Conclusions

Using the regionally disaggregated global energy system model with a detailed treatment of the electricity supply sector, this paper has derived the cost-optimal choice of electricity generation technologies in regional detail over the period to 2050 under the constraint of halving global energy-related CO_2 emissions in 2050 compared to the 2000 level. The major findings and notes are summarized below:

First, all the seven renewable power sources considered in this study and the two fossil power sources, coal and natural gas, will become cost-competitive in the long-term global generation system under the stringent CO_2 constraint used here. For these two fossil fuels to remain important power sources throughout the time horizon even under the stringent CO_2 constraint, the CO_2 resulting from fossil fuel combustion/conversion needs to be properly captured and sequestered. According to the simulation results, fossil-based power plants with CCS produce 75.5% of the total global fossil-based electricity generation in 2050. Among all the renewable power sources, hydro will continue to account for the largest share of the global electricity generation, followed by onshore wind, solar PV, solar CSP, and biomass. Offshore wind and geothermal sources are less competitive than the other renewable power sources.

Second, a future generation system in each world region will evolve over time in a very different manner to form a regionally highly diverse electricity supply structure. For example, the long-term generation system in the northeastern US and northern and eastern China consists mainly of coal, natural gas, nuclear, onshore wind, and solar PV, while that in Japan and Korea consists mainly of natural gas, nuclear, hydro, offshore wind, and solar PV. The main components of the Western Europe's long-term generation system include natural gas, nuclear,

biomass, hydro, onshore and/or offshore wind, and solar PV. Solar CSP plays an important role in the long-term generation system in the Middle East, Africa, Australia, the southern US, and western Asia, while hydro has a large share of the long-term generation system in Canada, Latin America, inland central and southern China, and southeastern Asia. Such a large regional difference in long-term generation systems is caused mainly by regional characteristics in terms of primary energy resource endowments, the need for a backup for variable renewables, the seasonal and daily load pattern, and the economics of CCS.

The results of this study must be interpreted with the following two limitations in mind. First, although the model solutions presented here are optimal in terms of cost under the stringent CO_2 constraint, electricity generation systems in the "real world" are designed to meet not only the goals of cost-effectiveness and reduced GHG emissions, but also other goals (e.g., of improved energy security and increased public acceptance), which are important but very difficult to consider in bottom-up optimization models like REDGEM70. Second, policy actions, targets, and incentives to reduce GHG emissions, to promote renewables, etc. have a large impact on the choice of technologies in the "real world", which are only partially considered in the model due to the lack of worldwide information. Nevertheless, this study is novel and significant in that the findings obtained from the regionally disaggregated results have important implications for the cost-optimal deployment of different electricity generation technologies under CO_2 constraints in many countries and regions.

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