Supplement

Long-term projections of global water use for electricity generation under the Shared Socioeconomic Pathways and climate mitigation scenarios

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S1. AIM/CGE regions

Table S1 lists the definitions of the Asia-Pacific Integrated/Computable General Equilibrium (AIM/CGE) regions, while Fig. S1 shows the distribution of the AIM/CGE regions.

S2. Regional results

Figure S2 shows regional water consumption differences under the recent-trend cooling case in 2100 among the Shared Socioeconomic Pathways (SSPs) and climate mitigation scenarios.

Figure S3 shows electricity generation under the baseline case for SSP1–5 in the Middle East. Figure S4 compares electricity generation for the SSPs and climate mitigation scenarios in the Middle East.

S3. Comparison with previous studies

S3.1. Comparison of water use for electricity generation with Davies et al. (2013), Kyle et al. (2013), Hejazi et al. (2014), and Bijl et al. (2016)

Figure S5 illustrates the water withdrawal and consumption for electricity generation in this study and previous studies. For clarity, only water withdrawal and consumption under the baseline and 3.4W cases are shown.

Similar to this study, previous studies on a global scale assessed the impacts of demand drivers that affect water use for electricity generation. Davies et al. (2013) focused on uncertainties in water use intensities, power plant cooling system changes, and adoption rates of water-saving technologies. Kyle et al. (2013) assessed the effects of climate change mitigation policies by comparing different climate mitigation levels and different energy source compositions. Hejazi et al. (2014) estimated future water use (including water use for electricity generation) under different socioeconomic scenarios characterized by possible economic, demographic, and technological improvements. These three studies applied the same methodology over a target period of 2005–2095 using the Global Change Assessment Model, an integrated assessment model. Bijl et al. (2016) estimated non-agriculture water use (including water use for electricity generation) under socioeconomic scenarios following the narratives of the SSPs and different efficiency assumptions from 1971 to 2100. There were several differences in the methods between this study and these previous studies, including the future scenarios and assumptions of future technological improvements. One of the largest differences was that we considered both socioeconomic changes and climate mitigation changes using the latest scenarios on global change based on the socioeconomic scenarios of the SSPs and climate mitigation scenarios based on representative concentration pathways (RCPs).

Our estimates of water withdrawal and water consumption without hydropower were mostly within the range of the previous estimates. However, water withdrawal and water consumption without hydropower under SSP5 were considerably larger than previous estimates. There are two explanations for this discrepancy. First, compared to previous studies, the composition of energy sources in SSP5 depended more on fossil fuels and biomass power, which required more water. Second, we did not consider any technological improvements beyond the shift in cooling system type (e.g., improvements in power plant efficiency and introduction of water-saving technologies). Based on the SSP narratives, the level of technological improvement is high in SSP1 and SSP5, low in SSP3 and SSP4, and moderate in SSP2. However, these technological improvements are expressed only by the technological improvement rate, which would have increased the uncertainty of our results; therefore, we did not take this factor into account.

Overall, water consumption for hydropower was larger than previous estimates, especially in the first half of the target period, because the electricity generation from hydropower in this study began to increase sooner compared with previous studies. In addition, SSP5 had a considerably larger water consumption with hydropower than previous estimates, similar to the case of water withdrawal and water consumption without hydropower. However, water consumption under RE_3.7 in Kyle et al. (2013) was similar, because the electricity generation share of concentrating solar power and geothermal power, which had considerable water consumptions, was very high.

S3.2. Comparison of water withdrawal for electricity generation with Fujimori et al. (2016a)

Figure S6 shows the global water withdrawal for electricity generation compared with the results of Fujimori et al. (2016a) and the industrial water withdrawal results of Hanasaki et al. (2013) (see Sect. S3.3). In Fujimori et al. (2016a), water withdrawal for electricity generation was estimated as part of industrial water withdrawal. Both studies used the SSPs as socioeconomic scenarios.

We used same electricity generation data as Fujimori et al. (2016a); however, our results were not the same. One possibly important difference between our study and Fujimori et al. (2016a) was their application of technological improvements. Fujimori et al. (2016a) applied technological improvement rates to water use intensity. They assumed that the technological improvement rates were consistent with SSP narratives; the rate of SSP3 and SSP4 was one-quarter while the rate of SSP2 was one-half those of SSP1 and SSP5. However, they found that their results were highly dependent on the technological improvement rate assumptions. For example, water withdrawal in SSP1 was smaller than that in SSP2, mainly due to the higher technological improvement rate in SSP1. In addition, they found that future technological improvements were difficult to predict and had large uncertainties.

In this study, we made assumptions on the shift in the proportion of cooling system types in use to represent one technological improvement. As mentioned in Sect. S3.1, we did not consider other technological improvements, such as power plant efficiency improvements or the introduction of water-saving technologies, to avoid increasing the uncertainty. Our water withdrawal and consumption results were generally larger than those of Fujimori et al. (2016a). However, our results would have been lower if we had considered additional technological improvements.

Fujimori et al. (2016a) applied different technological improvement rates to each SSP, consistent with the SSP narratives. Meanwhile, we applied the same cooling system type assumptions to all SSPs. By applying the same assumptions to all SSPs, we obtained the following results. SSP1 had the smallest water withdrawal and consumption among the SSPs, even though we did not consider differences in technological improvements in the SSPs. SSP2 and SSP4 had similar average water withdrawals and consumptions (Sect. 3.2). If we had considered differences in technological improvements, the average water withdrawal and consumption in SSP2 would have been smaller than that in SSP4, because the rate of technological improvement in SSP2 is higher than that in SSP4. The average water withdrawal and consumption in SSP3 was smaller than that in SSP2. However, the relationship between SSP2 and

SSP3 could have been reversed if differences in technological improvements had been considered, because the technological improvement rate in SSP2 is higher than that in SSP3. The technological improvement rate in SSP5 was the highest among the SSPs. However, great efforts would be required to make water withdrawal and consumption in SSP5 smaller than those of other SSPs, even if we had considered the differences in technological improvements, because they were at least two times larger than those of other SSPs. Therefore, if we had considered the differences in technological improvements among the SSPs, the relationships among SSPs might have changed from SSP1 < SSP3 < SSP2 = SSP4 < SSP5 to SSP1 < SSP2/SSP3 < SSP4 < SSP5.

S3.3. Comparison of water withdrawal for electricity generation with industrial water withdrawal in Hanasaki et al. (2013)

Water use for electricity generation is included in industrial water use. However, our results of water withdrawal for electricity generation under SSP1 and SSP5 in 2100 were about 2 and 3.5 times larger than the industrial water withdrawal in 2085 determined by Hanasaki et al. (2013) (Fig. S6). This was because Hanasaki et al. (2013) assumed high technological improvement rates in SSP1 and SSP5, similar to the assumptions of Fujimori et al. (2016). In addition, Hanasaki et al. (2013) did not consider the effect of energy source composition. In particular, in SSP5, electricity generation depends on fossil fuel, which requires a large amount of water. Therefore, the water withdrawal in SSP5 of Hanasaki et al. (2013) was much smaller than both of our results and those of Fujimori et al. (2016). Hanasaki et al. (2013) suggested that the water withdrawals in SSP1 and SSP5 were smaller than the other SSPs due to higher technological improvements. However, we found that the relationships among the SSPs changed by considering the effect of energy-related factors.

Table S1 Definitions of the AIM/CGE regions.

No.	Regions	(Code)	Countries
1	Oceania	XOC	AUSTRALIA, NEW ZEALAND
2	Canada	CAN	CANADA
3	EU25	XE25	AUSTRIA, BELGIUM, CYPRUS, CZECH REPUBLIC, DENMARK, ESTONIA, FINLAND, FRANCE, GERMANY, GREECE, HUNGARY, IRELAND, ITALY, LATVIA, LITHUANIA, LUXEMBOURG, MALTA, NETHERLANDS, POLAND, PORTUGAL, SLOVAKIA, SLOVENIA, SPAIN, SWEDEN, UNITED KINGDOM
4	Rest of Europe	XER	ALBANIA, ANDORRA, BOSNIA AND HERZEGOVINA, BULGARIA, CROATIA, FAROE ISLANDS, GIBRALTAR, HOLY SEE (VATICAN CITY STATE), ICELAND, LIECHTENSTEIN, THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA, MONACO, MONTENEGRO, NORWAY, ROMANIA, SAN, MARINO, SERBIA, SVALBARD AND JAN MAYEN, SWITZERLAND
5	Former Soviet Union	CIS	ARMENIA, AZERBAIJAN, BELARUS, GEORGIA, KAZAKSTAN, KYRGYZSTAN, REPUBLIC OF MOLDOVA, TAJIKISTAN, TURKMENISTAN, UKRAINE, UZBEKISTAN
6	Japan	JPN	JAPAN
7	United States	USA	UNITED STATES
8	North Africa	XNF	ALGERIA, EGYPT, LIBYAN ARAB JAMAHIRIYA, MOROCCO, TUNISIA
9	Rest of Africa	XAF	ANGOLA, BENIN, BOTSWANA, BURKINA FASO, BURUNDI, CAMEROON, CAPE VERDE, CENTRAL AFRICAN REPUBLIC, CHAD, COMOROS, CONGO, THE DEMOCRATIC REPUBLIC OF THE CONGO, CÔTE D'IVOIRE, DJIBOUTI, EQUATORIAL GUINEA, ERITREA, ETHIOPIA, GABON, GAMBIA, GHANA, GUINEA, GUINEA-BISSAU, KENYA, LESOTHO, LIBERIA, MADAGASCAR, MALAWI, MALI, MAURITANIA, MAURITIUS, MAYOTTE, MOZAMBIQUE, NAMIBIA, NIGER, NIGERIA, RÉUNION, RWANDA, SAINT HELENA, SAO TOME AND PRINCIPE, SENEGAL, SEYCHELLES, SIERRA LEONE, SOMALIA, SOUTH AFRICA, SUDAN, SWAZILAND, UNITED REPUBLIC OF TANZANIA, TOGO, UGANDA, WESTERN SAHARA, ZAMBIA, ZIMBABWE
10	China	CHN	CHINA, HONG KONG

11	India	IND	INDIA
12	Southeast Asia	XSE	CAMBODIA, EAST TIMOR, INDONESIA, DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA, REPUBLIC OF KOREA, LAO PEOPLE'S DEMOCRATIC REPUBLIC, MACAU, MALAYSIA, MONGOLIA, MYANMAR, PHILIPPINES, SINGAPORE, TAIWAN, THAILAND, VIET NAM
13	Rest of Asia	XSA	AFGANISTAN, AMERICAN SAMOA, BANGLADESH, BHUTAN, BRITISH INDIAN OCEAN TERRITORY, BRUNEI DARUSSALAM, CHRISTMAS ISLAND, COCOS (KEELING) ISLANDS, COOK ISLANDS, FIJI, FRENCH POLYNESIA, FRENCH SOUTHERN TERRITORIES, GUAM, HEARD ISLAND AND MCDONALD ISLANDS, KIRIBATI, MALDIVES, MARSHALL ISLANDS, FEDERATED STATES OF MICRONESIA, NAURU, NEPAL, NEW CALEDONIA, NIUE, NORFOLK ISLAND, NORTHERN MARIANA ISLANDS, PAKISTAN, PALAU, PAPUA NEW GUINEA, PITCAIRN, SAMOA, SOLOMON ISLANDS, SRI LANKA, TOKELAU, TONGA, TUVALU, UNITED STATES MINOR OUTLYING ISLANDS, VANUATU, WALLIS AND FUTUNA
14	Brazil	BRA	BRAZIL
15	Rest of South America	XLM	ANGUILLA, ANTIGUA AND BARBUDA, ARGENTINA, ARUBA, BAHAMAS, BARBADOS, BELIZE, BERMUDA, BOLIVIA, BOUVET ISLAND, CAYMAN ISLANDS, CHILE, COLOMBIA, COSTA RICA, CUBA, DOMINICA, DOMINICAN REPUBLIC, ECUADOR, EL SALVADOR, FALKLANDS ISLANDS (MALVINAS), FRENCH GUIANA, GREENLAND, GRENADA, GUADELOUPE, GUATEMALA, GUYANA, HAITI, HONDURAS, JAMAICA, MARTINIQUE, MEXICO, MONTSERRAT, NETHERLANDS ANTILLES, NICARAGUA, PANAMA, PARAGUAY, PERU, PUERTO RICO, SAINT KITTS AND NEVIS, SAINT LUCIA, SAINT PIERRE AND MIQUELON, SAINT VINCENT AND THE GRENADINES, SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS, SURINAME, TRINIDAD AND TOBAGO, TURKS AND CAICOS ISLANDS, URUGUAY, VENEZUELA, VIRGIN ISLANDS (BRITISH), VIRGIN ISLANDS (U.S.)
16	Middle East	XME	BAHRAIN, ISLAMIC REPUBLIC OF IRAN, IRAQ, ISRAEL, JORDAN, KUWAIT, LEBANON, OMAN, QATAR, SAUDI ARABIA, SYRIAN ARAB REPUBLIC, UNITED ARAB EMIRATES, YEMEN
17	Turkey	TUR	TURKEY

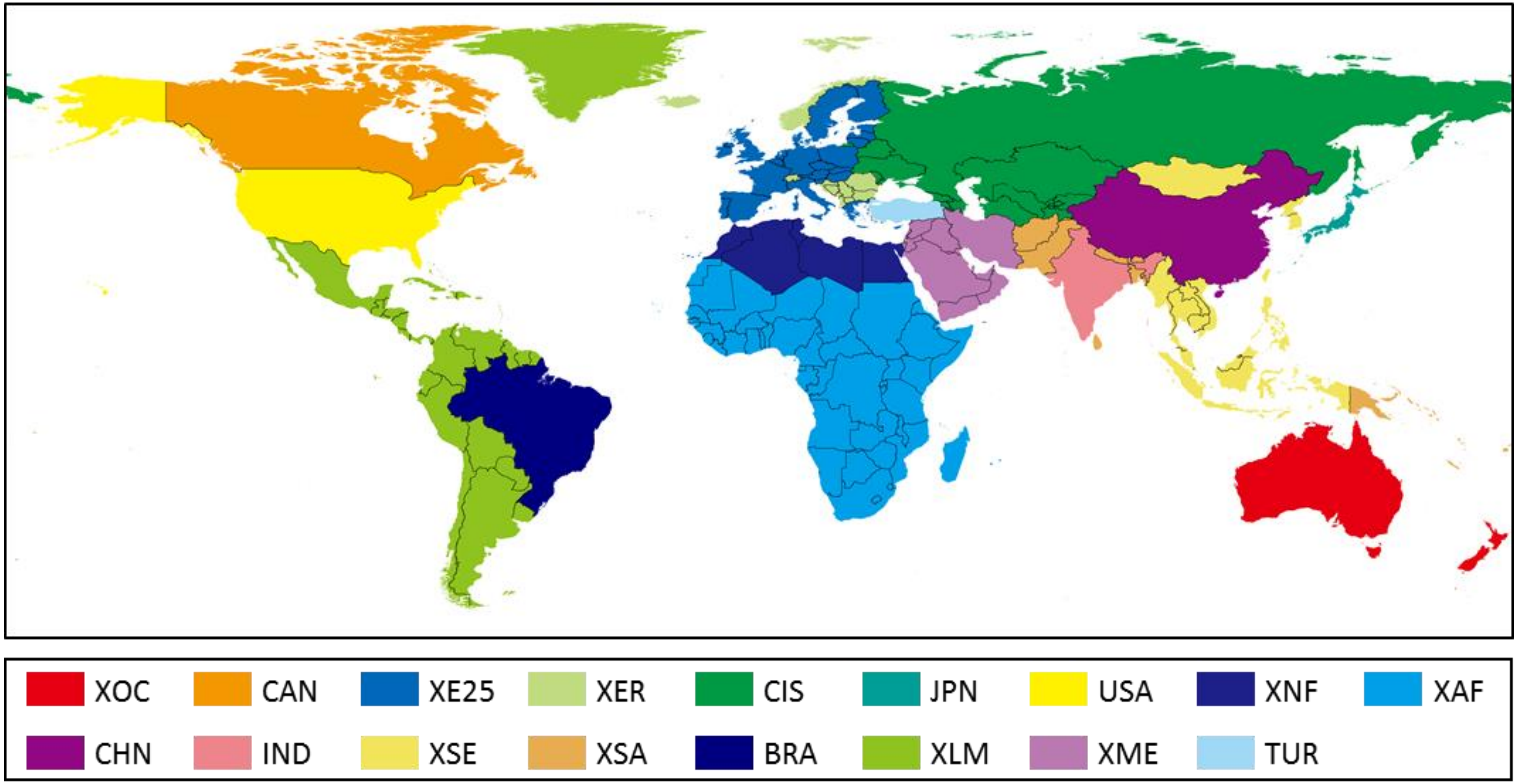

Figure S1 Distribution map of the AIM/CGE regions.

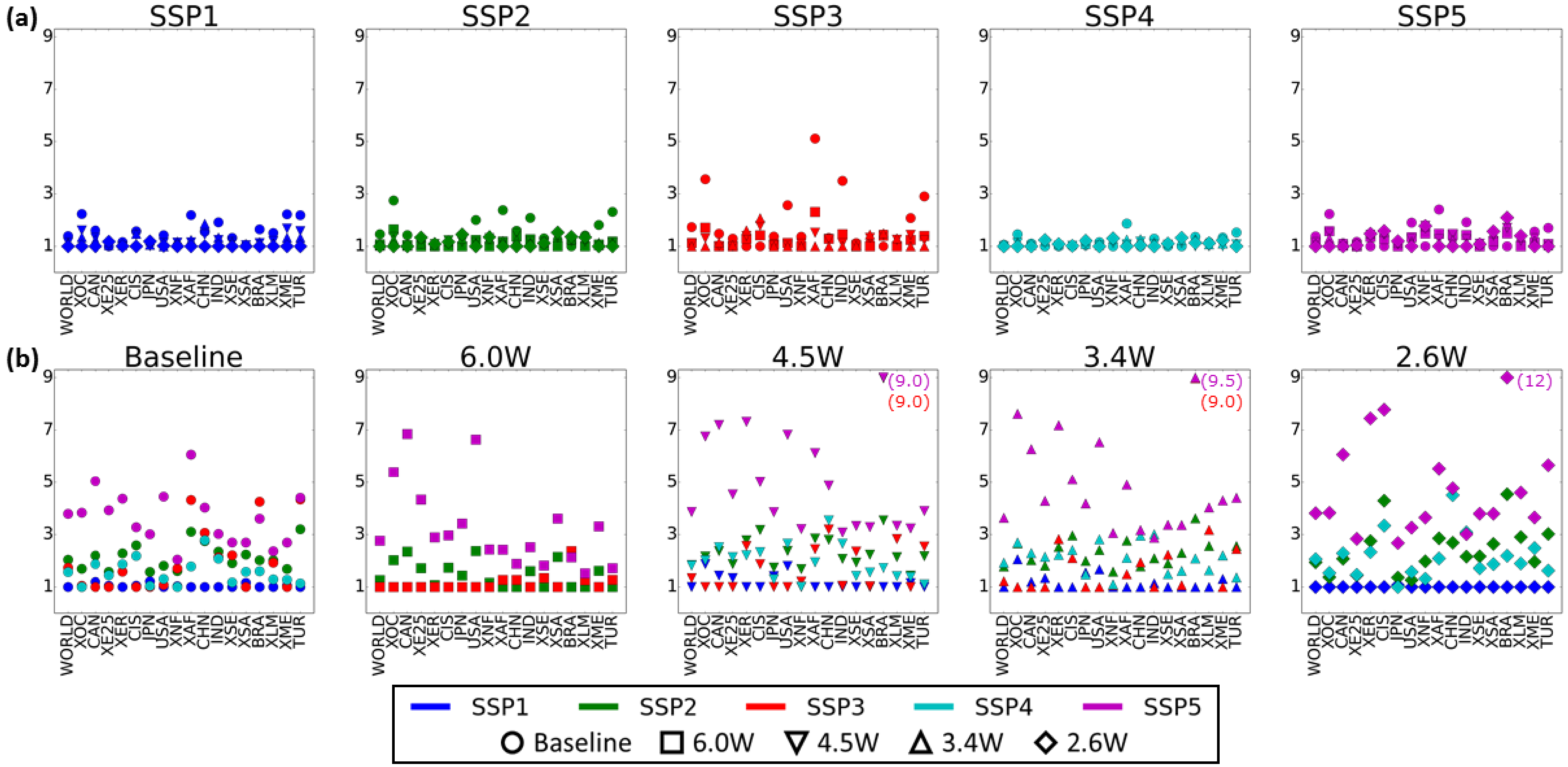

Figure S2 Regional water consumption differences under the recent-trend cooling case when (a) the Shared Socioeconomic Pathways (SSPs) is fixed and (b) the climate mitigation scenario is fixed in 2100. These values were calculated from the water consumption of each scenario divided by the minimum water consumption among scenarios. “1” represents the minimum water consumption among the climate mitigation scenarios in (a) and among the SSPs in (b). Values > 9 are plotted at 9 and noted in parentheses.

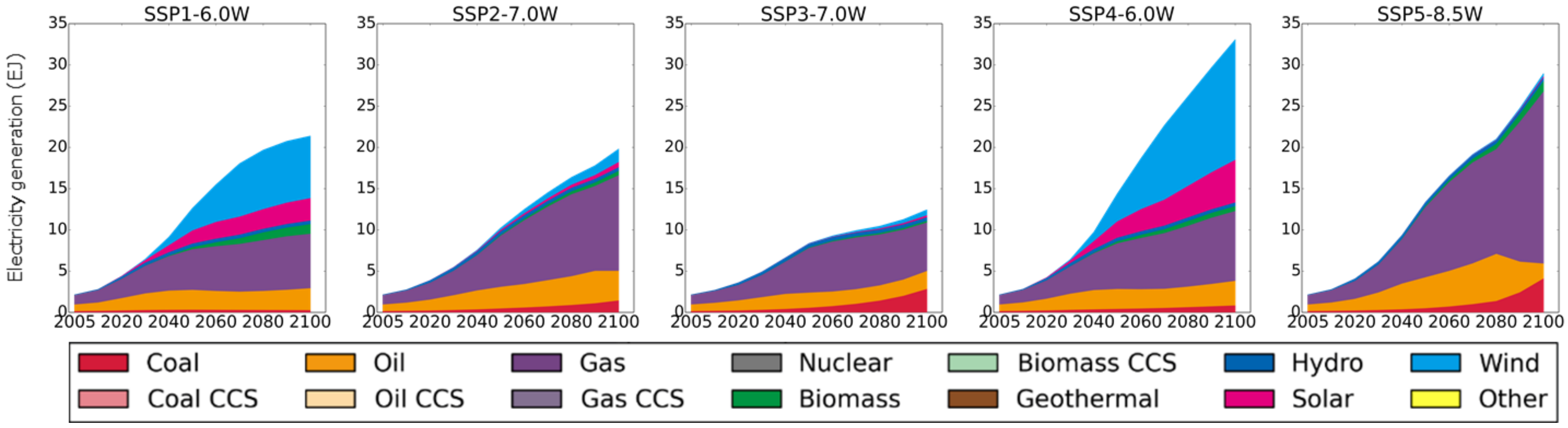

Figure S3 Electricity generation (EJ) by energy source under the baseline case for the SSPs in the Middle East.

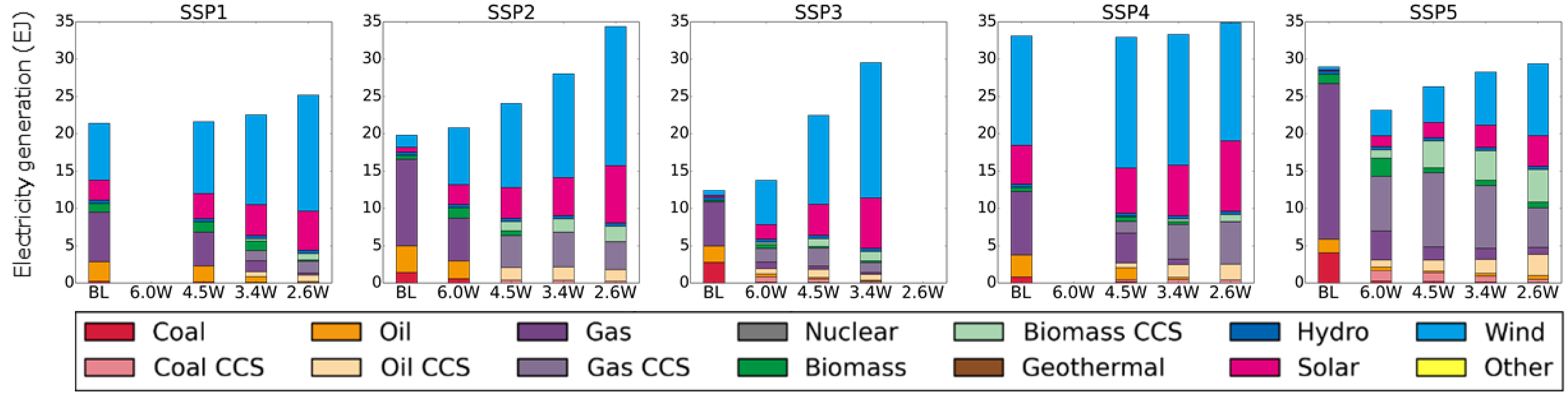

Figure S4 Electricity generation (EJ) by energy source in 2100 for the SSPs and climate mitigation scenarios in the Middle East. BL, baseline case.

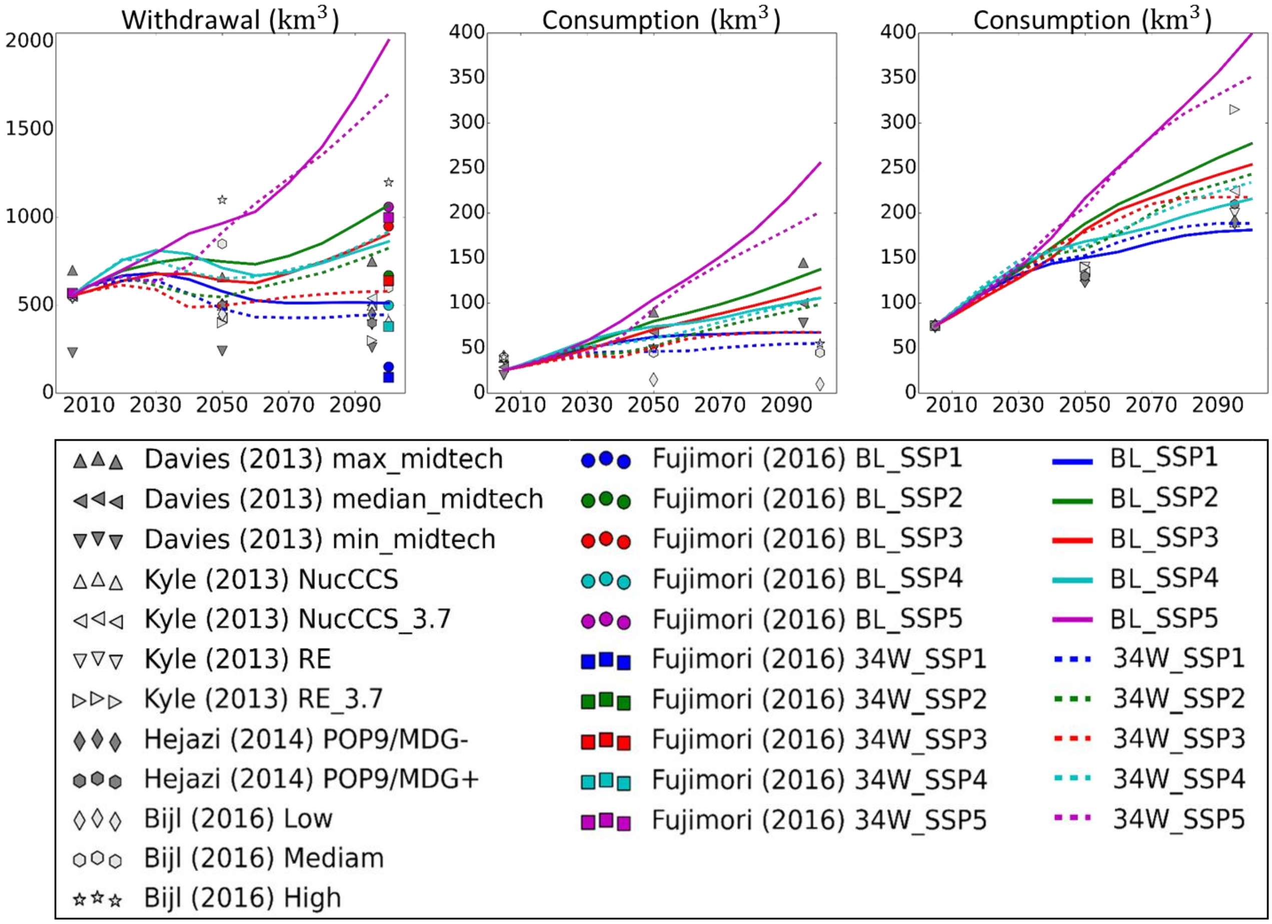

Figure S5 Projected total global water withdrawal (left), water consumption without hydropower (center), and water consumption with hydropower (right) compared with the results of previous studies. (Davies et al., 2013; Kyle et al., 2013; Hejazi et al., 2014; Bijl et al., 2016; Fujimori et al., 2016a). BL, baseline case. In Fujimori et al. (2016a), water withdrawal for electricity generation was estimated as part of industrial water.

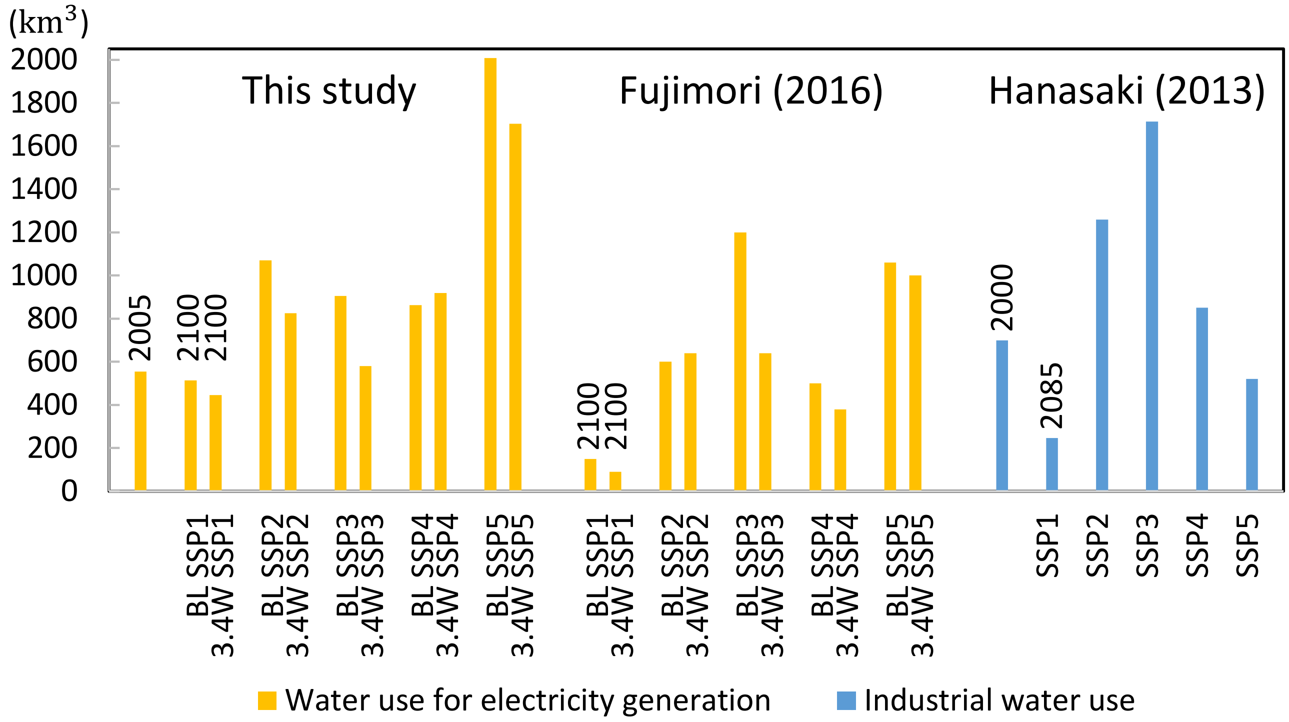

Figure S6 Global water withdrawal for electricity generation compared with the results of Fujimori et al. (2016a) and the industrial water withdrawal results of Hanasaki et al. (2013). BL, baseline case. In Fujimori et al. (2016a), water withdrawal for electricity generation was estimated as part of industrial water withdrawal.