

Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment

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Abstract This study assesses the effects of deep electricity decarbonisation and shifts in the choice of power plant cooling technologies on global electricity water demand, using a suite of five integrated assessment models. We find that electricity sector decarbonisation results in co-benefits for water resources primarily due to the phase-out of water-intensive coal-based thermoelectric power generation, although these co-benefits vary substantially across decarbonisation scenarios. Wind and solar photovoltaic power represent a win-win option for both climate and water resources, but further expansion of nuclear or fossil- and biomass-fuelled power plants with carbon capture and storage may result in increased pressures on the water environment. Further to these results, the paper provides insights on the most crucial factors of uncertainty with regards to future estimates of water demand. These estimates varied substantially across models in scenarios where the effects of decarbonisation on the electricity mix were less clear-cut. Future thermal and water efficiency improvements of power generation technologies and demand-side energy efficiency improvements were also identified to be important factors of uncertainty. We conclude that in order to ensure positive effects of

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decarbonisation on water resources, climate policy should be combined with technology-specific energy and/or water policies.

1 Introduction

In light of the Paris Agreement and the adoption of the Sustainable Development Goals (SDGs), the assessment of the water requirements of future decarbonisation pathways is important for ensuring the simultaneous sustainability of climate, energy and water policies. The Paris Agreement reinforced the aim of the international community to mitigate climate change and limit global warming to well below 2 °C, while ‘Climate action’ has been endorsed by the 2030 Agenda for Sustainable Development as one of the 17 adopted SDGs. At the same time, the way that the climate problem will be addressed strongly influences the prospects of meeting several other SDGs (von Stechow et al. 2016), with ‘Clean water and sanitation’ being one of them. Given the aim of the SDGs framework to reconcile several sustainable development objectives, the identification of synergies and trade-offs between climate change mitigation and the sustainability of energy and water resource systems is of increasing importance.

Amongst several uses, water is a crucial input for electricity generation. The electricity water requirements, and the impact of climate change mitigation on those, are affected by a wide range of factors such as the size of the electricity sector, the structure of the electricity mix and the type of cooling technologies used, such as once-through, recirculating or dry cooling (Kyle et al. 2013). The size of the power sector is expected to grow significantly in the next decades due to the observed growing electrification trend and the important role that electricity is expected to play for climate change mitigation (Williams et al. 2012; Krey 2014). The technology mix for achieving decarbonisation of electricity systems can be composed of various technologies (Luderer et al. 2014; Krey et al. 2014) with very diverse water requirements. These range from water-intensive thermoelectric power generation (fossil-, biomass- and nuclear-fuelled power plants) to variable renewables, such as wind or solar photovoltaics, with minimal water requirements. Finally, the choice between various cooling technologies with diverse water intensity levels is an important factor. This choice is largely influenced by policy and regulatory conditions, such as the Clean Water Act in the USA or the Water Framework Directive and the Freshwater Fish Directive in Europe. Also, the vulnerability of the electricity sector to water scarcity and variability is set to be aggravated by climate change (van Vliet et al. 2012, 2016; Bartos and Chester 2015), providing another driver for the adoption of new technologies.

Various studies analyse the effects of climate change mitigation on electricity water demand at case-study (Chandel et al. 2011; Macknick et al. 2012; Webster et al. 2013; Byers et al. 2014) or global scales (Kyle et al. 2013; Fricko et al. 2016; Mouratiadou et al. 2016a) via a scenario approach. Most of them analyse also the role of different cooling technologies (Byers et al. 2014; Fricko et al. 2016; Mouratiadou et al. 2016a). All previous modelling studies base their analysis on the use of one model per study. However, the insights provided by individual modelling studies are not always independent of the modelling approach or particular assumptions adopted by the study (Krey 2014). Therefore, multi-model intercomparison exercises are valuable in identifying robust patterns largely unaffected by different modelling approaches and parameter values (Krey 2014). An example of such an intercomparison exercise at regional level is the recent work of Srinivasan et al. (2017), which explores projections of water consumption and withdrawals for electricity generation in India till 2050. Apart from

modelling studies, work based on life cycle assessment (Fthenakis and Kim 2010; Meldrum et al. 2013) is very useful in estimating technology-specific water demand factors, but is typically static over time.

This study adds to the existing literature by performing the first, to our knowledge, multi-model intercomparison exercise on the effects of deep electricity decarbonisation on global electricity water demand over time. We consider ten scenarios which combine climate change mitigation strategies, along with adaptations in water and energy strategies. This allows us to analyse three important, yet uncertain, factors on estimates of future water demand for electricity generation until 2050: (a) electricity decarbonisation pathways induced by mitigation policy; (b) adoption shares of different cooling systems associated with water policy and vulnerability to climate change; (c) model assumptions reflecting real-world uncertainty. Our analysis is based on the use of five integrated assessment models (IAMs) of the energy–economy–climate interface. By using a comprehensive scenario and model set, this paper quantifies the effect of each of the three abovementioned factors on estimates of global water demand over time. Most importantly, it allows distinguishing robust patterns in future water demand and highlights the key factors of relevance for integrated water, energy and climate policy under uncertainty.

2 Methodology

2.1 Integrated assessment modelling

Our study uses an ensemble of five IAMs: GCAM (Edmonds and Reilly 1983; Brenkert et al. 2003; Wise et al. 2009), IMAGE (PBL 2014), POLES (Mima and Criqui 2015), REMIND (Bauer et al. 2012; Luderer et al. 2013, 2015; Bertram et al. 2015; Mouratiadou et al. 2016b) and WITCH (Bosetti et al. 2006; Emmerling and Drouet 2016). An important strength of IAMs is the adoption of an integrated systems perspective, which allows them to couple different model components representing for example the climate, energy, economic or land-use systems (Schwanitz 2013) and to enforce internal consistency by taking into account system interdependencies, such as supply- and demand-side feedbacks (Krey 2014). Additionally, these models tend to put a large focus on the technological representation of energy systems (Krey 2014) with comprehensive descriptions of energy carriers and conversion technologies. These characteristics allow IAMs to consider simultaneously the interlinkages across the water–electricity–climate nexus and to explicitly account for the underlying structural patterns of changes in electricity water demand, including demand patterns and the supply composition of the electricity sector (Mouratiadou et al. 2016a). In terms of their temporal and spatial resolution, the five IAMs operate at 5-year intervals from 2005 to 2100, and divide the world in a number of geo-political regions (32 regions in GCAM, 26 in IMAGE, 57 in POLES, 11 in REMIND and 13 in WITCH). Further details on the IAMs participating in this study are provided in the electronic supplementary material (ESM 1).

2.2 Representation of water demand

In this study, we harmonise the input data for the estimation of electricity water demand across all five IAMs, but allow for some diversity in the model-specific methodological representations. A summary of these representations is provided here, but the reader is referred to the first

section of ESM 1 for extensive details on the implemented methodologies and the used data, and ESM 2 for the data sets of all models.

The selected IAMs carry out an ex-post estimation of operational water demand for the electricity sector over time by combining exogenous information on the water requirements per electricity and cooling technology with endogenous information on the electricity mix. Operational water demand corresponds to water requirements associated with cleaning, cooling and other process-related needs that take place during electricity generation, such as flue gas desulfurisation (Macknick et al. 2011), but does not include water demand for fossil fuel extraction or for the irrigation of bioenergy crops. Water quantity and quality constraints, or the costs and technical characteristics of various cooling technologies, are not taken explicitly into account (see Section 4 for a discussion of the associated limitations).

All five models estimate both water withdrawal and water consumption. *Water withdrawal* is defined as the total amount of water which is taken from a water body, whereas *water consumption* corresponds to the amount of water withdrawal that is not returned to the original source and no longer available for reuse (consumed through evaporation) (Vickers 1999). Also, all models feature the principal cooling systems namely *once-through open systems* (using freshwater or sea water), *recirculating wet towers*, *pond cooling* and *dry towers*. Most models, with the exception of GCAM, do not consider efficiency losses for dry air cooling. Details on the definition of different cooling systems are given in ESM 1.

Thermal-power technologies can operate under all four cooling systems, featuring thus a large variation in water requirements depending on the cooling technology that is employed. Concentrated solar power (CSP) plants can operate with tower, pond or dry cooling, and withdrawal and consumption requirements are assumed to be equal to each other. Wind and solar photovoltaics operate with no or minimal water, while hydropower is assumed to withdraw no water but to consume considerable amounts. The five IAMs use the water demand coefficients reported by Macknick et al. (2011) and the cooling technology shares reported by Kyle et al. (2013). Information on the technological coverage and assumed water withdrawal and consumption coefficients per technology for all models are shown in ESM 2. Average water intensities per unit of electricity production, estimated by taking into account the electricity mix and the exogenous coefficients per technology, are shown in ESM Fig. 1.

2.3 Scenarios

Our study considers ten scenarios combining, on the one hand, the dimension of climate change mitigation and, on the other hand, the dimension of adaptation to water policy and climate change.

The dimension of climate change mitigation is encapsulated by five alternative options for the electricity system, developed by Luderer et al. (in review). The scenario design aims to reflect the flexibility in decarbonisation strategies for the power sector since these may rely heavily on nuclear, carbon capture and storage (CCS), or renewable energy sources. Our scenario set includes a baseline scenario with no climate policy and four deep decarbonisation scenarios in line with the 2 °C target. In the decarbonisation scenarios, cumulated net direct CO₂ emissions of the power sector in the period 2011–2050 have been constrained to 240 Gt CO₂, while in the baseline scenario these are equal to about 600 to 750 Gt CO₂ depending on the model. The emissions constraint results in an at least 80% reduction of electricity sector emissions in 2050 relative to 2010, when emissions were equal to about 11 Gt CO₂/year. Modelling teams have achieved this low carbon budget via the imposition of

carbon prices, which are applied also to sectors other than power supply, in order to avoid inter-sectoral leakage. The IAMs take into account the costs needed for energy transformations including the costs of primary energy sources, investment costs, operation and maintenance costs, investment cost reductions due to learning-by-doing for wind and solar, costs for the expansion of transmission grids, investments into electricity storage technologies and the carbon tax when applicable.

The five mitigation scenarios are as follows:

1. *Base*: baseline scenario with no emissions constraint and full technology availability.
2. *FullTech*: mitigation scenario with full technology availability.
3. *Conv*: mitigation scenario with a decarbonisation strategy that is largely based on conventional technologies (CCS and nuclear); this is due to limited deployment of variable renewable electricity sources (solar and wind) via a constraint of a maximum allowance of up to 10% of combined share of wind and solar power supply per region.
4. *CCS*: mitigation scenario relying heavily on CCS; in this scenario, there is limited deployment of variable renewable electricity sources (implemented as in the Conv scenario) in combination with a phase-out of nuclear power, implemented by assuming no further investments into nuclear capacities after 2010.
5. *Ren*: mitigation scenario resulting in a high share of variable renewable power supply; in this scenario, we assume a nuclear phase-out (implemented as in the CCS scenario) combined with a ban on CCS technologies.

Changes in the adoption shares of different cooling technologies, due to adaptation to policy or climate change, are represented by two alternative pathways:

1. *Static*: no change in the shares of the different cooling technologies over time; the IAMs use the ‘Base year’ values on cooling system technology mixes reported in table 2 of Kyle et al. (2013) over the whole study period.
2. *Adaptive*: the shares of dry, recirculating and seawater cooling systems increase over time; the IAMs start in 2005 from the ‘Base year’ values (as in the Static scenario) and transition to the ‘Future’ values reported in table 2 of Kyle et al. (2013). The implementation of the transition slightly differs between models due to different model specifications and is described in detail in the first subsection of ESM 1.

3 Results

3.1 Overview of water demand across scenarios and models

The decarbonisation scenarios tend to result in lower water withdrawals compared to the Base scenario, although their water footprints vary considerably (Figs. 1 and 2). The Ren scenario is clearly associated with the lowest water withdrawal requirements. In cumulative terms during the period 2005–2050, these can be as low as almost half the water withdrawals of the Base scenario (Fig. 2). Cumulative withdrawals for the CCS scenario are higher than those of the Ren scenario and equivalent to about 60–70% of those of the Base scenario. The FullTech scenario is associated with highly variable results across models. Nevertheless, the associated water withdrawals are higher than those of the Ren and CCS scenarios and lower than those of the Conv and Base scenarios, when analysing cumulative withdrawals (Fig. 2) or model-specific results (ESM Fig. 4). The Conv scenario is the decarbonisation scenario resulting in the highest withdrawals, which are also associated with an increasing trend in time. Although cumulative withdrawals for 2005–2050

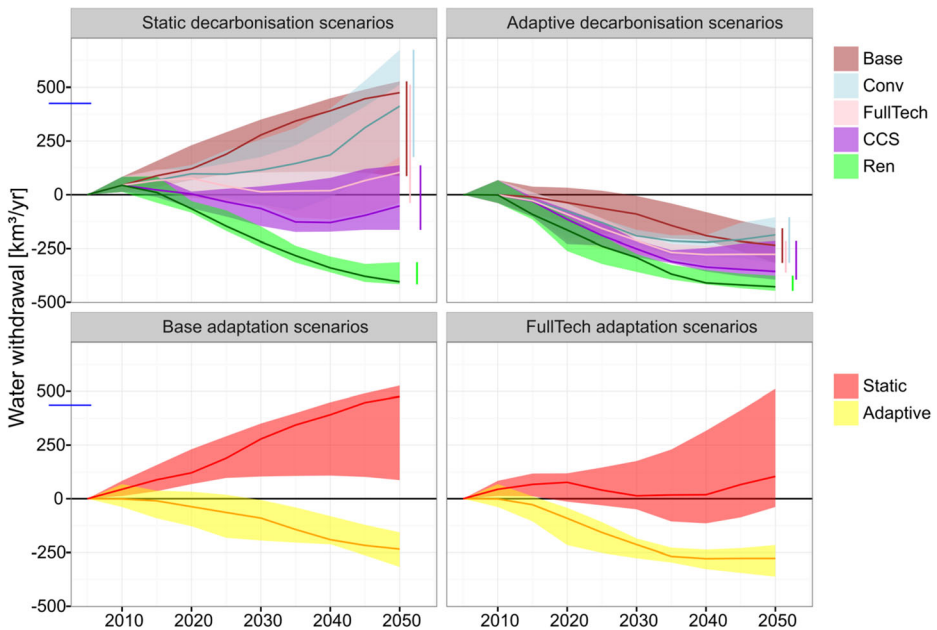


Fig. 1 Changes in electricity water withdrawals (differences of 2050 to 2005 values). The horizontal blue lines indicate the level of water withdrawals in 2005. The coloured lines show the median values per scenario and time step

are still lower than those of the Base scenario (Fig. 2), absolute withdrawals tend to supersede those of the Base scenario towards mid-century (Fig. 1, ESM Fig. 4).

Patterns are similar but more variable when analysing water consumption, as opposed to withdrawal. Cumulative water consumption between 2005 and 2050 from all technologies except hydropower tends to be lower for the Ren scenario and followed by the CCS, FullTech, Conv and then Base scenarios (Fig. 2). However, the differences across scenarios are less evident than those associated with the water withdrawal indicator, and more variable between models (ESM Fig. 5). Also, the scenario associated with the greatest variability between models for this indicator is the Ren scenario. Regarding hydropower water consumption, no clear patterns across decarbonisation scenarios can be deduced from our results. Some models assume fixed hydropower expansion across scenarios, others result in higher requirements in the decarbonisation cases and others in lower ones (ESM Fig. 2, ESM Fig. 5). Nevertheless, in reality, the estimation of water consumption for hydropower is highly intricate due to its dependence on reservoir size and local climatic conditions, as well as on the multiple uses of reservoirs and the methodology used to allocate evaporation to electricity generation (Gleick 1992; Macknick et al. 2012; Bijl et al. 2016). Therefore, associated estimates are inherently highly uncertain.

A change in the cooling technology mixes results in a massive reduction of water withdrawals both in time and also compared to the equivalent static scenarios across all model–scenario combinations (Fig. 1, ESM Fig. 3, ESM Fig. 4). This pattern is more pronounced in mitigation scenarios with higher water requirements such as Base, Conv and FullTech, where cumulative withdrawals are about halved under the adaptive scenarios (Fig. 2). On the other hand, water consumption is slightly increased under the adaptive scenarios (Fig. 2). This comes as no surprise since the water consumption of recirculating systems, which are expanded under the adaptive scenarios, is typically higher than this of once-through systems (see ESM 2 for the associated

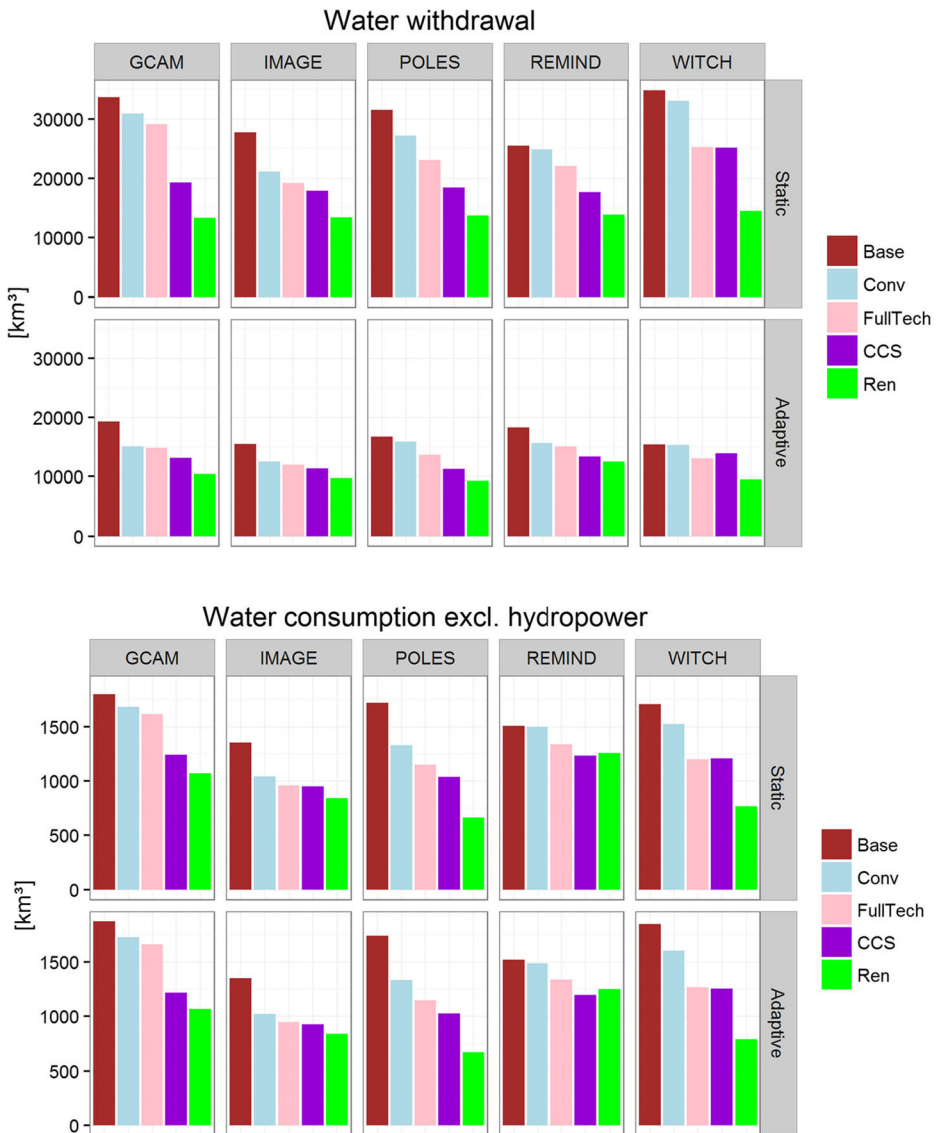


Fig. 2 Cumulative electricity water demand across scenarios and models in the period 2005–2050. Water consumption for hydropower is in the range of 3000–4000 km³. It is shown separately in ESM Fig. 2 in order to improve readability of this figure

values). However, as these changes are minimal, we will not analyse in more detail the differences across static and adaptive scenarios for water consumption in the remainder of this paper.

3.2 Decomposition of water demand into electricity demand and supply factors

In order to understand the patterns identified in Section 3.1, we decompose changes in water demand into changes in total electricity demand (associated with the scale of the electricity sector) and changes in the average water intensity per unit of electricity production (associated

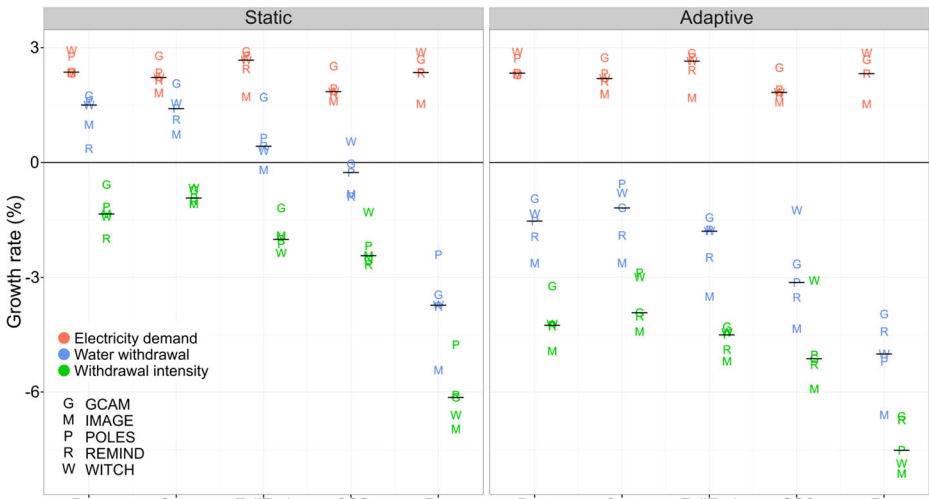


Fig. 3 Decomposition of changes in electricity water withdrawal into changes in electricity demand and in average water withdrawal intensity (average annual growth rates in the period 2005–2050). The horizontal black lines show the medians per scenario and variable

with the structure of the electricity sector and the cooling technologies adopted). We use the following decomposition identity for both withdrawal and consumption (below demonstrated for withdrawal, but identical for consumption), using average yearly growth rates:

$$\text{Water withdrawal} = \text{Electricity demand} \cdot \left(\frac{\text{Water withdrawal}}{\text{Electricity demand}} \right)$$

In all model–scenario combinations, we observe an increase of electricity demand over time (Fig. 3, ESM Fig. 6, ESM Fig. 7) imposing an upward trend to water demand. This is combined with a decrease in the water withdrawal intensity of electricity production (Fig. 3) imposing a downward trend. Despite the important scale effect of increasing electricity demand, differences across scenarios are primarily explained by differences in the water intensity factors. Specifically, we observe greater water withdrawal intensity improvements for the Ren scenario, followed by the CCS, FullTech and lastly the Conv and Base scenarios, due to changes in the electricity mixes as discussed in more detail in the following section. Results are similar for the water consumption indicator although, as discussed in Section 3.1, the differences across scenarios are less clear-cut and the variability between models is greater (ESM Fig. 7).

Water withdrawal intensities are the key explanatory factor also for differences between the static and the adaptive scenarios (Fig. 3). The adaptive scenarios are related to consistently lower average water withdrawal intensities which explain the associated significantly lower water withdrawal requirements. This effect is more pronounced for mitigation scenarios with higher water demand (e.g., Base, FullTech, Conv) since these scenarios rely more on thermo-electric technologies, for which the choice of cooling technology (once-through or other) greatly affects water cooling requirements.

3.3 Water demand intensities and the structure of electricity supply

As we saw in Section 3.2, water demand intensities are an important explanatory factor of our results. These intensities are determined by different characteristics of electricity supply

systems, such as electricity mixes, shares of cooling systems per electricity technology and improvements in water usage efficiency over time. In order to identify the effect of these different factors, we decompose water demand per electricity (Fig. 4, ESM Fig. 8) and cooling technology (ESM Fig. 9).

Electricity mixes are key in understanding differences across decarbonisation scenarios. The Base scenario, associated with the highest water demand, is characterised by an increase in coal- and gas-based electricity generation, and consequently in the associated water requirements over time (Fig. 4). On the other hand, all decarbonisation scenarios lead to a reduction of fossil-based power production without CCS. This effect results in lower water demand for these technologies, but the choice of technology portfolio that substitutes them largely determines the water footprints of the alternative scenarios.

In the Ren and CCS scenarios, in addition to fossils without CCS, nuclear power is also almost eliminated and substituted primarily by either renewables (Ren scenario) or fossils (mainly gas) and biomass with CCS (CCS scenario) (Fig. 4). The water withdrawal savings due to the phase out of fossils without CCS and nuclear supersede by far the minimal increases of water withdrawals for solar CSP or biomass in the Ren scenario. That is also the case for the CCS scenario, where water withdrawal increases for fossils and biomass with CCS are lower due to a switch from coal to gas which is less water-intensive. As a result, the Ren scenario is the scenario with the lowest withdrawals and the CCS scenario the one with the second lowest ones. In the FullTech and Conv scenarios, where the technology portfolios are less restricted, we observe greater variability in the composition of the electricity mixes. Fossil fuels without CCS are also eliminated in these scenarios, but since there are no restrictions in the deployment of nuclear power, this features much more prominently and raises significantly both water withdrawals but also variability across models (Fig. 4). The adoption of nuclear, and also fossil fuels with CCS, is higher in the Conv scenario due to limitations in the deployment of variable renewables. Therefore, this decarbonisation scenario is the one corresponding to the highest water withdrawals.

Results are similar regarding water consumption (Fig. 4). However, since CSP is one of the most water-consuming technologies, the associated water consumption is considerably increased in the Ren scenario. For most models, this increase is still lower than the reductions due to the elimination of fossils and nuclear, but the variability across models is significant.

In the adaptive scenarios, the massive improvements in technology-specific water withdrawal intensities reduce the importance of electricity mixes for the results, while the effect of changes in the adoption of cooling technologies dominates. The water withdrawal requirements are reduced significantly for thermoelectric technologies across all decarbonisation cases. That is due to the drastic reduction of once-through cooling water requirements on which they used to rely on in the static scenarios (ESM Fig. 8, ESM Fig. 9). Water withdrawal increases are observed for wet tower cooling systems, which are more dominant in the adaptive scenarios (ESM Fig. 9).

3.4 Uncertain water demand patterns

The previous sections discuss findings that are generally robust across the range of participating models. Despite these robust patterns, the variability of results across models under certain scenarios is significant. In this section, we investigate in more detail the explanatory factors of this variability.

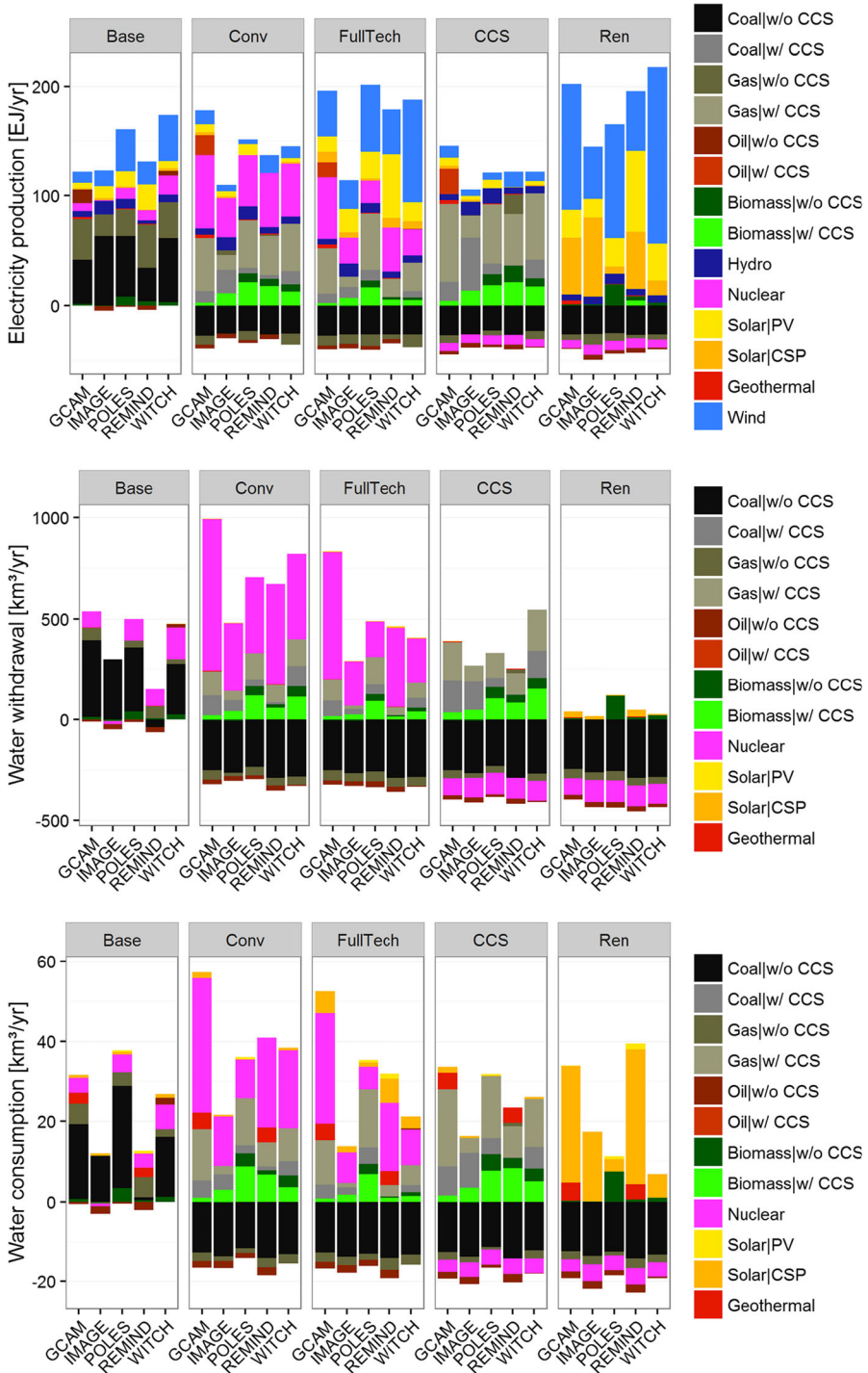


Fig. 4 Changes in electricity production and water demand specified by electricity generation technology for the static scenarios (differences of 2050 to 2005 values)

We observe that the large fluctuations in water demand estimates are due to significant differences in the electricity demand and the water withdrawal intensity of water intensive electricity technologies. Generally, the variation is greater in cases where both of these factors vary considerably. That is the case for nuclear in the FullTech and Conv scenarios, and coal without CCS for the Base scenario (Fig. 4, ESM Fig. 10), which are the scenarios associated with the highest variability across models, as we saw in Section 3.1. For example, in the Conv Static scenario, we observe that the increase of water withdrawals for nuclear between 2005 and 2050 ranges by more than a factor of two between the models in the highest and lowest ends (749 km³/year for GCAM, 378 km³/year for POLES and 338 km³/year for IMAGE) (ESM Fig. 10).

Differences in electricity demands per technology across models can be attributed to differences in energy efficiency improvements and the shares of these technologies in the electricity mix. For example, in the Conv scenario, the increase in nuclear deployment between 2005 and 2050 ranges almost by a factor of two between the models in the higher and lower ends (67 EJ/year for GCAM, 46 EJ/year for POLES and 35 EJ/year for IMAGE) (ESM Fig. 10). That is primarily due to differences in total electricity demand (in 2050 232 EJ/year for GCAM, 187 EJ/year for POLES and 147 EJ/year for IMAGE) and slight differences in the share of the technology in the electricity mix (in 2050 33% in GCAM, 31% in IMAGE and 30% in POLES).

In the same scenario (Conv), changes in nuclear water withdrawal intensities also vary considerably (ESM Fig. 10). These are almost unchanged compared to 2005 in GCAM and reduced by about 27% in POLES which assumes exogenous improvements in the coefficients. Significant reasons for such variations can be improvements in water or thermal efficiencies or technological coverage and deployment. For example, the large variation on the withdrawal intensities for coal, with REMIND and IMAGE featuring the lowest withdrawal intensities (ESM Fig. 10), is because these two models capture reductions due to thermal efficiency improvements and also represent and adopt significantly more water-efficient technologies, such as integrated gasification combined cycle and combined heat and power, compared to other models.

The variation in water consumption across models is primarily caused by the high variability in the adoption and intensities of hydropower, solar CSP in the Ren scenario, and Nuclear in the Conv and FullTech scenarios (ESM Fig. 11). The variability associated with hydropower is due to differences in the assumed consumption coefficients. While most models use the globally uniform coefficients reported in Macknick et al. (2012), IMAGE is using regionally differentiated data based on Mekonnen and Hoekstra (2012) and Torcellini et al. (2003) (see ESM of Bijl et al. 2016). Regarding solar CSP, IMAGE assumes that the water efficiency of wet towers improves by 28% between 2015 and 2040, for all scenarios, technologies and regions, and therefore has a lower intensity than other models. Also, the increase in the deployment of CSP in the Ren scenario varies significantly across models. The reasons for the variability of water consumption for nuclear are similar to those regarding water withdrawal described above.

4 Limitations

There are some caveats to our analysis. Our models lack an endogenous representation of water quantity and quality constraints, as well as a representation of the costs and other techno-economic characteristics of cooling types. For example, retrofitting a pulverised coal-fired

power plant from once-through to dry cooling implies a 3–4% reduction in net plant efficiency, capital costs of \$129–722 million, and annual operational costs of \$3–12 million (Loew et al. 2016). These factors are not negligible and may therefore be important determinants of the expansion of water-saving electricity technologies and the choice of cooling systems. As demonstrated by the analysis of Loew et al. (2016), such decisions are complex and made in function of the age of the plant, the marginal costs of water savings and the water scarcity of a region.

Also, upstream water demand, such as for fossil fuel extraction, or most importantly for the irrigation of bioenergy crops, is not accounted for. The water requirements for growing bioenergy crops for electricity generation vary significantly depending on the crop used, the agricultural practice and the climate at the location of production (Gerbens-Leenes et al. 2009). As shown by Gerbens-Leenes et al. (2009) for a set of 13 crops, these requirements can range from 46 to 396 m³/GJ of electricity, but can be reduced substantially with the use of residues and process by-products (Berndes 2002; Mathioudakis et al. 2017). Given these uncertainties, water requirements for growing bioenergy crops have not been included in our analysis, but it should be noted that these can be substantial and may affect significantly the water footprint of mitigation scenarios that rely heavily on bioenergy.

Our study focused on the effects of supply side variations of the electricity system until 2050. As shown by Mouratiadou et al. (2016a) and Fricko et al. (2016), high electricity demand, e.g., triggered by economic growth or population increase, may result in higher water demand under a climate change mitigation scenario compared to a baseline scenario in the second half of the century, if this demand is fulfilled by water intensive technologies such as nuclear.

We acknowledge that water impacts are inherently regional in nature, and that regional variation is of importance. In their majority, IAMs at this stage of their development lack the necessary granularity to represent water impacts and decisions at the most appropriate scale. On the other hand, these models are most appropriate for analysing climate policy decisions that have a cumulative global effect which cannot be analysed by regional studies. A regional analysis of our results is hampered by the lack of uniform definitions of world regions across the individual IAMs and is beyond the scope of this study. We expect our findings on the water requirements of decarbonisation scenarios and the identification of robust versus uncertain factors associated with estimates of electricity water demand to be generally applicable, although the magnitude of results may vary across regions. For example, ESM Fig. 12 shows that for three key regions faced with water scarcity and high electricity demand currently and/or in the future (China, India, USA), differences in cumulated water withdrawals between scenarios tend to be similar to those of the global figures (see Fig. 2). Further research looking in more detail into the effects of decarbonisation on regional water demand patterns would be of great value.

Some of our decarbonisation scenarios rely heavily on the wide adoption of specific technologies, such as nuclear, variable renewables or CCS, that may be subject to implementation barriers. We refer the reader to Iyer et al. (2015), Krey et al. (2014) and Tavoni et al. (2012) for a broader discussion of the feasibility of climate policy based on different decarbonisation technologies; to Pietzcker et al. (2017), Sovacool (2009), Luderer et al. (2014) and Fischer (2012) for a discussion on the prospects of variable renewables; to Koelbl et al. (2014) for an analysis in relation to CCS; and to Toth (2008) for a discussion regarding nuclear.

Finally, the lack of a comprehensive database on fresh water use by the electricity sector and the challenge of sparse data on water coefficients resulted in variations in the input data

and assumptions adopted by the different models. It should be noted that, although variation in the electricity generation mixes is due to model structure and cost assumptions, variation in results associated to water are also due to scarcity of reliable and uniform water data sets at country and regional levels. Such data-related uncertainties should be overcome with time and future research should aim at compiling comprehensive datasets at the plant, country and regional levels in order to address this issue.

5 Conclusions

This paper assesses the effects of deep electricity decarbonisation, as well as shifts in power cooling technology adoption, with the use of five IAMs in order to identify robust and uncertain patterns with regards to global electricity water demand. In summary, we find that climate change mitigation has co-benefits for water resources primarily due to the phase-out of water-intensive fossil-based, and in particular coal-based, thermoelectric power generation. However, these co-benefits vary substantially across scenarios and models depending on the electricity decarbonisation pathway that will be adopted.

A robust pattern in our results is that wind and solar photovoltaic represent a win-win option for both climate and water resources. In fact, in a case where variable renewables are widely adopted, the water savings induced by decarbonisation can be comparable to those induced by a shift into less water-intensive power cooling technologies. On the other hand, nuclear expansion may result in increased pressures on water resources. This finding suggests that investments in variable renewables and phase-out of fossil and nuclear capacities would contribute simultaneously towards climate change mitigation, reduce impacts on the water environment and safe-guard the sector against climate change-induced hydrological risks.

Despite these robust patterns, the model intercomparison exercise provided useful insights with respect to the most crucial factors of uncertainty regarding future water demand. The variability of the water demand coefficients within individual technologies highlights the uncertainty associated with the thermal and water efficiency improvements of power generation technologies (e.g., for coal), as well as technical and climatic conditions (e.g., for hydropower). In scenarios with greater flexibility in the choice of the electricity portfolio, model results on the electricity mixes and the associated water requirements were significantly more variable. This reflects the great leeway to decarbonise the electricity sector and implies that for the effects of decarbonisation to be clearly positive for water resources, dedicated technology-specific policies are required. Except supply side changes, we observe that the extent of demand-side adjustments under decarbonisation is a factor that differs between models and reflects actual uncertainty on the energy efficiency improvements that can be materialised. In any case, demand-side measures can also assist in reducing the water footprint of the electricity sector as a whole.

The analysis of two distinct water demand indicators showed that some of the findings on the water withdrawal indicator do not hold for the water consumption one. First, although a switch away from once-through fresh water cooling systems reduces massively water withdrawal, it may increase water consumption. Also, in cases with high reliance of the power sector on CSP with recirculating cooling systems, although water withdrawals are expected to be lower, water consumption may increase.

This paper identifies robust and uncertain patterns and key factors of relevance for integrated water, energy and climate policy. That is currently of utmost importance given the

Paris Agreement stipulating climate change mitigation but also the wider endorsement of the SDGs encouraging policy integration across different fields of environmental action. From a policy perspective, we conclude that, although decarbonisation tends to reduce water demand, climate policy may need to be combined with technology-specific energy and/or water policies. Such policies may focus on restricting the expansion of water-intensive technologies, encouraging the deployment of wind and solar photovoltaics, and/or enforcing environmental flow protection. This is particularly important in water-scarce locations that expect high growth of both water and electricity demand in the future, and where decarbonisation may rely heavily on technologies such as nuclear or fossil- and biomass-fuelled power plants with CCS.

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