Supplementary Information

Energy sector water use implications of a 2 °C climate policy

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S1: MESSAGE integrated assessment modeling framework

Model overview

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) integrated assessment model (IAM) is a global systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development [1-3]. Developed at the International Institute for Applied Systems Analysis (IIASA) for more than two decades, MESSAGE is an evolving framework that, like other global IAMs in its class (e.g., MERGE, ReMIND, IMAGE, WITCH, GCAM, etc.), has gained wide recognition over time through its repeated utilization in developing global energy and emissions scenarios [4,5].

The MESSAGE model divides the world up into eleven regions (Figure S1.1, Table S1.1) in an attempt to represent the global energy system in a simplified way, yet with many of its complex interdependencies, from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Trade flows (imports and exports) between regions are monitored, capital investments and retirements are made, fuels are consumed, and emissions are generated. In addition to the energy system, the model includes also the other main greenhouse-gas emitting sectors, agriculture and forestry.

MESSAGE tracks a full basket of greenhouse gases and other radiatively active gases – CO2 , CH4 , N2O , NOx , volatile organic compounds (VOCs), CO, SO2, PM, BC, OC, NH3, CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca, and SF6 – from both the energy and non-energy sectors (e.g., deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning). In other words, all Kyoto gases plus several others are accounted for.

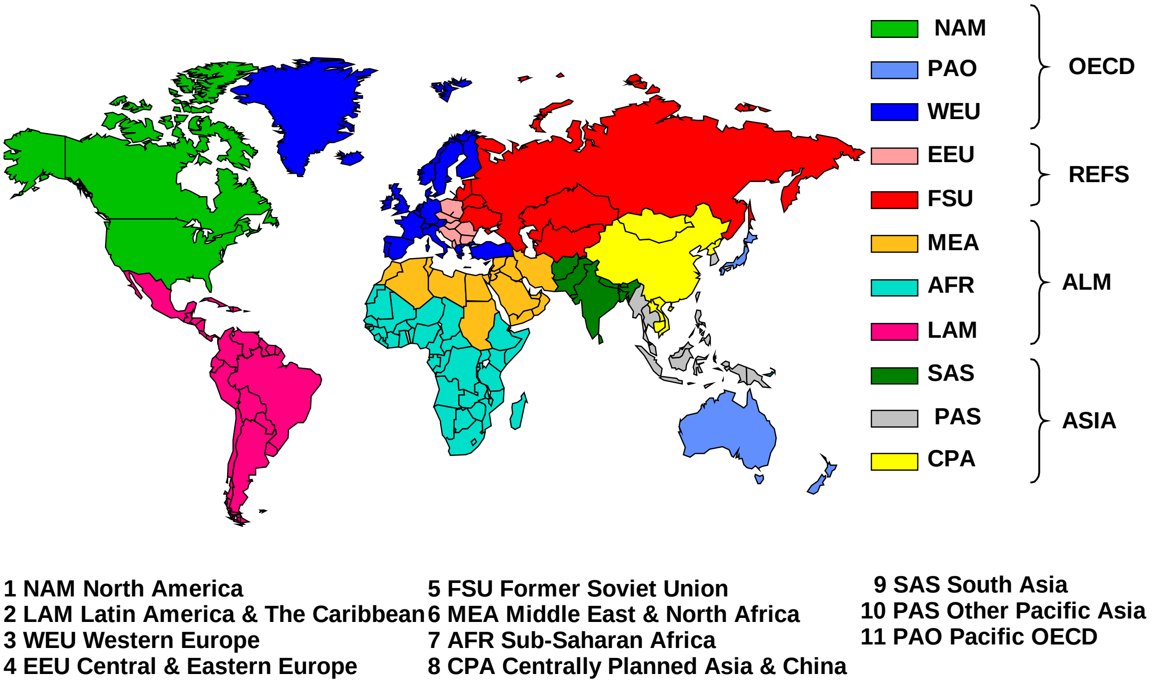

Figure S1.1: Regional representation of the MESSAGE model

Table S1.1 Countries included in the MESSAGE macro-regions

11 MESSAGE regions	**Definition (list of countries)**
NAM	**North America** (Canada, Guam, Puerto Rico, United States of America, Virgin Islands)
WEU	**Western Europe** (Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
PAO	**Pacific OECD** (Australia, Japan, New Zealand)
EEU	**Central and Eastern Europe** (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Estonia, Latvia, Lithuania)
FSU	**Former Soviet Union** (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CPA	**Centrally Planned Asia and China** (Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
SAS	**South Asia** (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)
PAS	**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 (China), Thailand, Tonga, Vanuatu, Western Samoa)
MEA	**Middle East and North Africa** (Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen)
LAM	**Latin America and the Caribbean** (Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)
AFR	**Sub-Saharan Africa** (Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGE can make use of. In the course of a model run, MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints (both technological and policy), while minimizing total discounted energy system costs over the entire model time horizon (1990-2110). It does this based on a linear programming, optimization solution algorithm. The representation of the energy system includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, clustering effects (technological interdependence) and the phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). Combined, these factors can lead to “lock-in” effects [6, 7] and path dependency (change occurs in a persistent direction based on an accumulation of past decisions). As a result, technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to alter its course.

Important inputs for MESSAGE are technology costs and technology performance parameters (e.g., efficiencies and investment, variable, and O&M costs). For the scenarios included in this paper, technical, economic and environmental parameters for over 100 energy technologies are specified explicitly in the model. Costs of technologies are assumed to decrease over time as experience (measured as a function of cumulative output) is gained. For assumptions concerning the main energy conversion technologies see the following references: Riahi et al. [8], Nakicenovic and Swart [4], Riahi et al. [2], and van Vliet et al. [3]. For information on carbon capture and storage technologies specifically, see Riahi et al. [9].

MESSAGE is able to choose between both conventional and non-conventional technologies and fuels (e.g., advanced fossil, nuclear fission, biomass, and renewables), and in this respect the portfolio of technologies/fuels available to the model obviously has an important effect on the model result. In the version of the model used in this study, we consider a portfolio of technologies whose components are either in the early demonstration or commercialization phase (e.g., coal, natural gas, oil, nuclear, biomass, solar, wind, hydro, geothermal, carbon capture and storage, hydrogen, biofuels, and electrified transport, to name just a subset). Notably, this portfolio includes bio-CCS, a technology that can potentially lead to negative emissions (i.e., permanent underground storage of CO2 which was originally pulled out of the atmosphere by photosynthesis). Exceedingly futuristic technological options, such as nuclear fusion and geo-engineering, are, however, not considered.

Other important input parameters for our modeling include fossil fuel resource estimates and potentials for renewable energy. For fossil fuel availability, the model distinguishes between conventional and unconventional resources for eight different categories of (oil, gas, coal) occurrences [2, 10]. For renewable potentials we rely on spatially explicit analysis of biomass availability and adopt the assumptions discussed in Riahi et al. [2].

Price-induced changes in energy demand (i.e., elastic demands) are also modeled in MESSAGE via an iterative link to MACRO, a top-down, macroeconomic model of the global economy [11]. Through an iterative solution process, MESSAGE and MACRO exchange information on energy prices, energy demands, and energy system costs until the demand responses are such that the two models have reached equilibrium. This iterative solution process focusses on each of the six end-use demand categories in the model: electric and thermal heat demands in the industrial, residential, commercial, and transportation sectors. This process is parameterized off of a baseline scenario (which assumes some autonomous rate of energy efficiency improvement) and is conducted for all eleven MESSAGE regions simultaneously. Therefore, the demand responses motivated by MACRO are meant to represent the additional (compared to the baseline) energy efficiency improvements and conservation that would occur in each region as a result of higher prices for energy services. The macro-economic response captures both technological and behavioral measures (at a high level of aggregation), while considering the substitutability of capital, labor, and energy as inputs to the production function at the macro level.

Further and more detailed information on the MESSAGE modeling framework is available, including documentation of model set-up and mathematical formulation [1, 2] and the model’s representation of technological change and learning [9, 12, 13].

Connection to MAGICC reduced-complexity global climate model

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), version 6 [14, 15], has been used in this study to estimate the climate system impacts of the varying greenhouse gas emission trajectories of the scenarios in the ensemble. MAGICC is a reduced-complexity coupled global climate-carbon cycle model that runs on a personal computer ([14-16] and www.magicc.org). In its standard form, MAGICC calculates internally consistent projections for atmospheric concentrations, radiative forcing, global annual-mean surface air temperature, and ocean heat uptake, given emissions trajectories of a range of gases (CO2, CH4, N2O, CO, NOx, VOCs, SO2, and various halocarbons, including HCFCs, HFCs, PFCs, BC, OC, NH3, and SF6), all of which are outputs from MESSAGE. The climate model in MAGICC is an upwelling-diffusion, energy-balance model, which produces outputs for global- and hemispheric-mean temperature. Climate feedbacks on the global carbon cycle are accounted for through the interactive coupling of the climate model and a range of gas-cycle models. MAGICC has been used in all IPCC Assessment reports, dating back to 1990, and its strength lies in its ability to replicate the more complex global climate models that run on supercomputers [15]. For our analysis, we use MAGICC6 in a probabilistic setup [14, 17] that is consistent with the IPCC Fourth Assessment Report, Working Group 1. In this setup, MAGICC probabilistically [17] spans the uncertainties in carbon-cycle [18], climate system [19] and climate sensitivity [20, 21] of the IPCC AR4. Its response is constrained by historical observations of hemispheric land/ocean temperatures [22] and historical estimates for ocean heat-uptake [23]. With this probabilistic approach, transient exceedance probabilities for each scenario are computed. Temperature increase relative to pre-industrial values is computed relative to the average temperature between 1850 and 1875.

S2: Inclusion of thermoelectric water use in the MESSAGE model

Review of thermoelectric water use

There are some studies that give a broad overview of impacts of water use in the energy sector (e.g. Williams et al [26], 2013, Gleick, 1994 [27]); however, the bulk of water requirements within the energy system are constituted by thermoelectric generation. As a result, the majority of the literature emphasizes quantification of thermoelectric water use. This section presents an overview of thermoelectric water use found in the literature. Sources and data are summarized in the excel spreadsheet included as a Supplementary Data file. Below, we discuss key characteristics of water use by different energy technologies.

Steam-cycle generation utilize significant amounts of water to produce the steam that drives the electric turbine. The thermal processes accompanying operation of thermoelectric generation also produce a significant amount of waste heat. To maintain operating efficiencies and prevent long-term damage caused by excessive heat, thermoelectric generation must incorporate cooling systems. Water is typically used as the working fluid in the cooling system, providing needed heat transfer capabilities. Different cooling technologies exist, but can be classified into three main types: once-through, closed-loop, and air-cooled systems. Once-through cooling technology, as the name suggests, involve passing water through the cooling system once, and then returning the water to its source. Conversely, closed-loop systems re-circulate water that is withdrawn. Air-cooled systems rely on air for cooling, and therefore provide an opportunity to reduce energy system reliance on water.

Confounding trade-offs between the cooling technologies exist. For example, significantly more water must be withdrawn in once-through systems as compared to closed-loop, in order to enable once-through systems to continuously provide cooling services. Conversely, the recirculation of water in closed-loop systems results in more evaporative losses, or higher water consumption. Cooling towers are usually needed for the release of the evaporated water, which adds to the cost of closed-loop systems. Differing management practices and environmental regulations for the effluent streams also impacts technology performance. Once-through systems return water to the aquatic environment at much higher temperatures than closed loop systems, which may require development of ancillary cooling ponds to prevent excessive thermal pollution. Although air-cooling provides an opportunity to break the reliance on water, these systems are the most expensive, and operate at lower efficiencies than water-cooled technology. As a result, air-cooled fossil fuel thermoelectric generators emit more greenhouse gas emissions per unit of fuel than those that are water-cooled. Hybrid cooling options do exist, and have the potential to overcome tradeoffs between cooling technology types, although hybrid options are the most complicated and have the highest capital costs.

One of the main determinants of a power plant’s cooling requirement is its thermal efficiency: the less waste heat produced, the lower the water intensity should be. The use of combined-cycles provides an opportunity to significantly increase power plant efficiency by incorporating the waste-heat into the power generation process. The impact on water use can be profound. For example, natural gas combined-cycle (NGCC) plants require only a third of the water used by conventional single-cycle steam units [24, 25].

Nuclear power plants, all of which currently rely on the steam cycle, operate at lower steam pressures and temperatures in comparison to conventional fossil fueled steam power plants. This results in larger steam volume requirements, which in turn requires more cooling water relative to the power output [24]. Furthermore, nuclear power plants cannot emit heat like fossil fuel power plants through flue gases, resulting in yet more heat having to be discharged via the cooling system. The deployment of nuclear power plants is thus complicated by the fact that the location of the power plant must also offer access to sufficient volumes of water for cooling purposes in case of emergencies. Safety-restrictions on maximum steam temperature and therefore resulting low efficiencies, are the main reasons for the high water requirements for nuclear power plants, which are typically 20-40% higher than those of coal-fired power plants [26]. Future high efficiency designs could possibly reach water intensity levels comparable to the current fossil technology level [27].

Concentrated solar power (CSP) plants function similar to steam turbine power plants, and therefore also require cooling. The lower net steam cycle efficiency of CSP plants in comparison to fossil-fueled steam units result in comparatively higher water intensity [28]. In fact, the water use intensity of CSP systems is comparable to that of nuclear power plants [26], although the literature review shows a broad range. Large-scale CSP facilities mostly employ closed-loop systems. Dry cooling can also be used to reduce water requirements by 90 %, but the resulting parasitic load to operate the cooling fans (approximately 4 – 5 % of production) needs to be compensated by installing larger plants. Cost increases of employing a dry-cooled system over a closed loop system, range from 2 - 9 %. Hybrid cooling systems, a combination of dry and wet-cooling systems, are an option for CSP plants, and have the potential to reduce water requirements in comparison to the conventional closed-loop system by 50 % [28].

Significant uncertainty in the water used by geothermal power plants is observed in the literature. This comes from the fact that there are different system designs resulting in very different water intensities. Hydrothermal flash systems operate at around 182 degrees Celsius, consuming only 0.01 gal/kWh. Hydrothermal Binary systems which operates between 74-182 degrees Celsius employ working fluid, either isobutene or isopentane as well as a geothermal fluid, whereby the working fluid is used as a heat transfer medium in a closed loop system. The consumption of these systems is also very low at around 0.27 gal/kWh. To access deeper geothermal resources, existing fractures are further fractured by means of injecting water. These enhanced geothermal systems operate between 175-225 degrees Celsius, requiring 0.51gal/kWh [29]. The fourth type of system, geo-pressured geothermal technology, makes use of reservoirs that contain hot water as well as natural gas. The process and therefore the water consumption level is similar to that of the hydrothermal systems after the hot water has been separated out from the natural gas. The majority of systems in operation today employ wet or dry cooling towers, and therefore closed loop systems [29]. Only in more arid regions is dry cooling used. Based on an overview of current installed capacities, small units (~5MW) are usually binary or back-pressure units. Medium sized installations of around 30MW are usually flash systems, while the larger systems of around 45MW are usually dry-steam systems. Only a few countries have realized projects over 100MW. The current average geothermal plant size is around 20.6MW, the majority of the plants using flash or dry-steam systems [30]. If the exploitation of hydrothermal resources is to be further expanded, this will require the upscaling of medium-low temperature development projects employing binary plants [31]. More ambitious targets will even require enhanced geothermal systems. Yet, our literature review shows that the large differences in coefficients can be partly traced back to differing accounting methods, resulting in the mean consumption moving towards the lower end of the range, as some sources also account for geothermal liquids, which in fact are drawn from freshwater resources [30].

Some thermoelectric generation types require additional water for services beyond cooling, and the water use coefficients are adjusted to address these further requirements. Integrated gasification combined cycle (IGCC) plants are an example, and require more water than conventional combined-cycle plants due to the gasification process (i.e., slurrying and desulphurization). Furthermore, super-critical pulverized coal (PC) power plants are more efficient than conventional sub-critical PC power-plants, but super-critical plants often require more water due to the flue gas desulphurization (FGD) process. Wet or dry FGD technologies are considered in the coefficients applied in this paper, and can increase the water requirements by approximately 10% [26]. Wet scrubbing is the most common FDG system employed worldwide, making up to 80% of total installed capacity. Dry-scrubbers are in fact semi-dry scrubbers of which two main types exist: spray dry scrubbers and circulating dry scrubbers. Dry systems make up slightly less than 10% of global capacity and use approximately 60% less water than wet FGD systems. Nevertheless, unlike wet FGD systems, all of the water used in the semi-dry scrubbing process is evaporated. Circulating dry scrubbers not only require less water than wet-scrubbers, they also absorb more SO3 as well as oxidized mercury.

Power plants employing carbon capture and storage (CCS) also incur water penalties. For example, with the addition of CCS for PC plants using closed-loop cooling systems, water consumption per unit of output increases by 90% [24]. This is due to the fact that the CO2 absorption process requires large amounts of cooling water, therefore creating additional load for the cooling tower. In fact, adding CCS to subcritical and supercritical plants increases the FGD makeup water consumption alone by 40-50% [32]. Adding CCS systems to IGCC and NGCC plants, results in 46% and 76% higher water consumption for plants employing closed-loop cooling systems [24].

Another factor adding to the general uncertainty of water use estimates for thermoelectric power plants is the fact that certain types of plants are only used for peak load generation. These systems can spend significant time idling. However, cooling circulation pumps usually operate at full capacity, resulting in possible deviations in the estimated amounts of water withdrawn, depending on the method used to determine water intensity.

A summary of the range in water use intensity for each technology observed in the literature and the sources are provided in the Supplementary Data file (excel spreadsheet).

Representation of thermoelectric water use

The water coefficients used for the analysis should reflect values based on the literature, but at the same time need to be adapted to the specific technologies used within MESSAGE. For example, technological learning is a key feature of long-term energy models, and is expected to impact the heat rate of power generation over time. Even though developments can be taken into account when integrating the various water coefficients into the model based on values obtained from the literature review, the information available does not necessarily provide consistent coefficients for the technologies accounted for in MESSAGE. More specifically, in the literature consumption and withdrawal coefficients for technologies are not always provided by a single source. Therefore, applying a formal approach in the form of an algorithm circumvents any deviations due to different underlying assumptions, providing coefficients which lie within the ranges established in the literature review and can be adapted where necessary to reflect region specific traits.

Delgado and Herzog [33] explain how water consumption and withdrawals can be calculated for both once-through and closed-loop cooling systems for different technologies based on the basic principal of how thermal power plants function. The simplified version of the formula highlights the three main parameters as a function of the heat rate, which is the amount of energy needed generate one kWh of output:

$$i = \alpha \cdot (\varepsilon - \beta) + \delta \tag{S2.1}$$

where ε represents the heat-rate (kWh heat/kWh net power output), α represents how efficiently the cooling technology utilizes water (m^3/kWh heat), β represents other heat outputs (heat content of electricity and other heat losses such as with flue gases; kWh heat/kWh net power output), and δ represents water requirements other than for cooling (m^3/kWh net power output). According to this equation the water requirement for a specific power plant is determined by the amount of heat dissipated through the cooling system (ε - β), the type of cooling system employed (α) and other plant specific water requirements (δ), such as flue-gas-desulfurization, gasification processes or boiler feed make-up water. Parameterization of the coefficients for various thermoelectric power plants can be found in Delgado and Herzog [33]. Most sources do not explicitly detail these “other” water requirements, but provide several approximations of water required for the non-cooling processes in power-plants. This information is critical for understanding how much freshwater is required by plants even if an air-cooled or sea-water fed once-through cooling system is employed. By tracking the different components of water use, we are able to estimate thermal pollution $(\varepsilon - \beta)$: the amount of heat ejected from the power plant that is incorporated into the environment.

The diagrams (Figure S2.1) below summarize the water withdrawal- and consumption coefficients for thermoelectric power plants estimated from the literature, as well as the estimates obtained from the approach proposed by Delgado and Herzog [33]. For this analysis, dry- and sea-water-cooling are two further cooling technologies taken into account. Effects of cooling ponds are not directly depicted, as withdrawal figures for power plants using cooling ponds can obtrude data. The water is essentially circulated within an enclosed body of water, therefore withdrawals should only really account for makeup water required due to evaporation. As plant efficiency is a prime determinant of the water requirement, the heat rate for each technology has been added to help relate technologies.

An upper and lower value of water use coefficients for each technology (dark-blue lines; triangle markers depict upper- and square markers depict the lower-coefficient) are included in the MESSAGE analysis. The higher water intensity coefficient is applied generally to regions, where either the operation and maintenance of power plants is generally not level to that of Western Europe or the United States, for which the medium coefficient is assumed, or where the mean ambient temperature across the year is relatively high, therefore reducing the effectiveness of the cooling system. The lower coefficient is used as an indicator of the potentially achievable water intensity assuming technological improvements of the current cooling technologies. In some regions, even though it may be possible to realize these efficiencies technically, the operational conditions may not permit achieving these low intensities. Data gaps are reflected by the lack of a grey bar, which indicates the literature data range. In such cases, water use coefficients were established based on the technology specific heat-rate and cross comparing water requirements between other technologies with similar characteristics, as well as by looking at available data for other cooling systems.

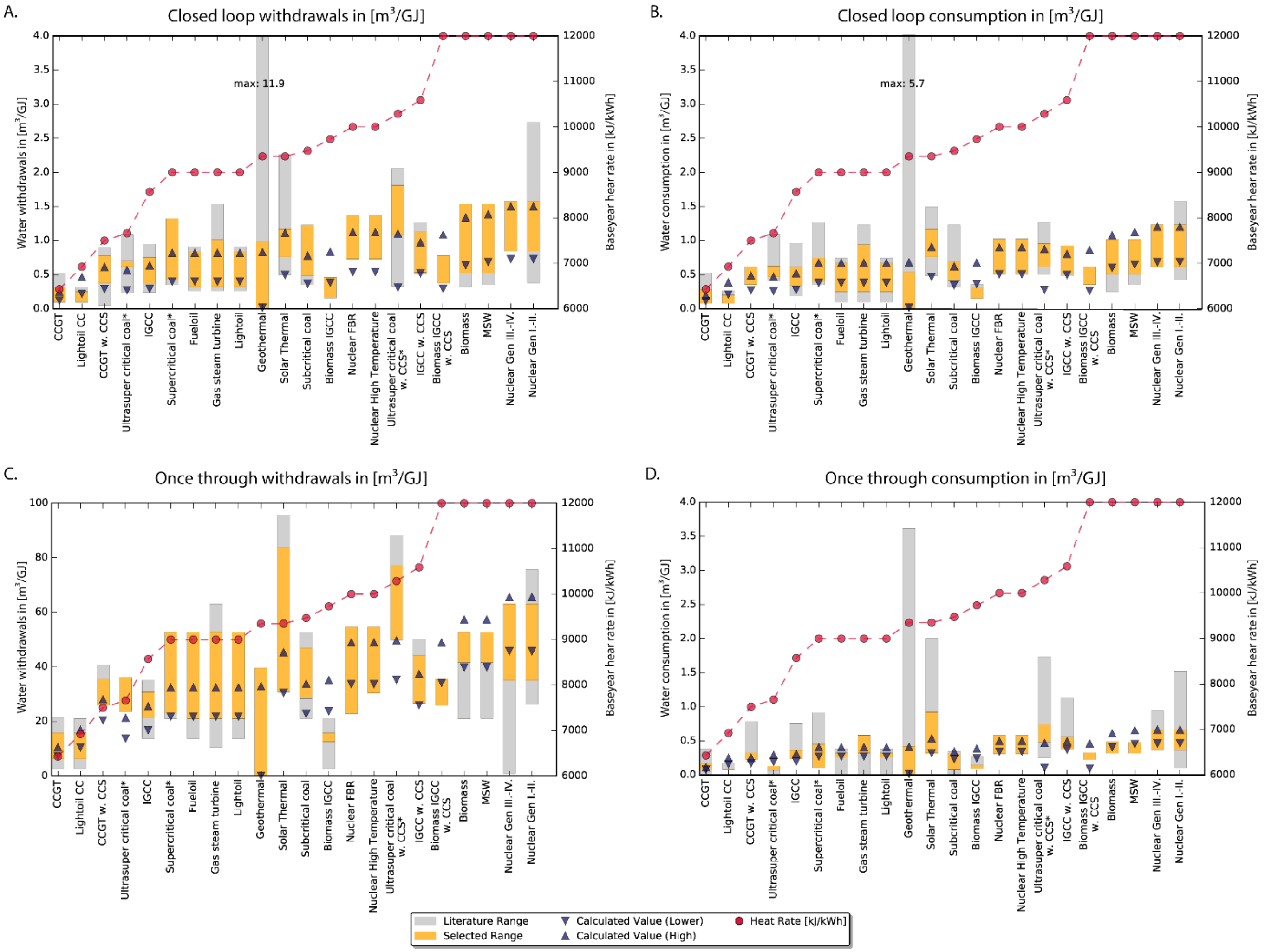

Figure S2.1: Range in water intensity coefficients for thermoelectric power plants obtained from the literature review and calculated with Equation (S2.1) for: (A) withdrawal, closed loop cooling systems; (B) consumption, closed loop cooling systems; (C) withdrawal, once-through cooling systems; and (D) consumption, once through cooling systems.

Non-thermal generation, fuel processing and resource extraction

Non-thermal electricity generation technologies also require access to water. Wind turbines and conventional photovoltaic systems need relatively miniscule amounts of water for cleaning purposes. Hydropower plants also consume water resources due to their effect on evaporation [34]. Storage reservoirs increase the water area in contact with the air, resulting in more water lost to evaporation. These requirements are, however, associated with significant uncertainty, mainly due to the wide range in system types. Run-of-river type facilities do not typically increase the rate of evaporation above that which occurs naturally. Reservoirs also often serve purposes other than the production of electricity, such as for irrigation supply, recreation or flood control, and that the electricity production may even be limited due to environmental regulations downstream. Rather than completely excluding the water required by hydro-power plants, a suitable compromise suggested is that the fractional water use attributed to hydroelectricity production should be less or equal to the capacity factor, which represents the ratio between the actual power output over a given time period, to the energy that could have been generated were the plant operating at the full nameplate capacity in the same time period.

Apart from the electricity generation processes themselves, resource extraction and fuel and heat generation processes also contribute towards the overall water requirements of the energy system, albeit not being as significant as those of the electricity generation processes. Past literature

[35] has not focused as intensively on evaluating these other parts of the energy chain compared to the thermoelectric generation sector, resulting in limited sources giving broader overviews across several technologies within a certain sector.

A summary of the range in water use intensity for each extraction and processing technology observed in the literature is provided in the Supplementary Data file (excel spreadsheet).

S3: Alternative cooling technology scenario parameterization

The base-year distribution of thermoelectric cooling technologies for each technology group and in each region is fixed based on an assessment of current distributions by Davies et al [36]. Thus, in future periods, shifts in the distribution of cooling technology types are achieved solely through shifts to technology groups with different distributions. Transitioning from once-through cooling systems towards air-cooled technology represents a potential option for decreasing the water intensity of energy supply. Utilizing sea water provides another means of reducing energy sector reliance on freshwater resources. Opportunities to address water challenges in the energy sector through cooling technology transitions are examined by constructing an alternative scenario.

Figure S3.1 depicts the baseline cooling technology scenario investigated in this paper. In the alternative scenario, once-through systems for thermoelectric technology are phased out over the 2040 – 2060 period, with the affected capacity simulated to transition towards a combination of air and sea water cooling technologies along a linear trajectory. As air cooling affects energy production efficiency, we explore potential tradeoffs with water use by calculating expected impacts on electricity production. The efficiency losses assumed for each technology are estimated from a technical study by the US EPA [37] and provided in Table S3.1.

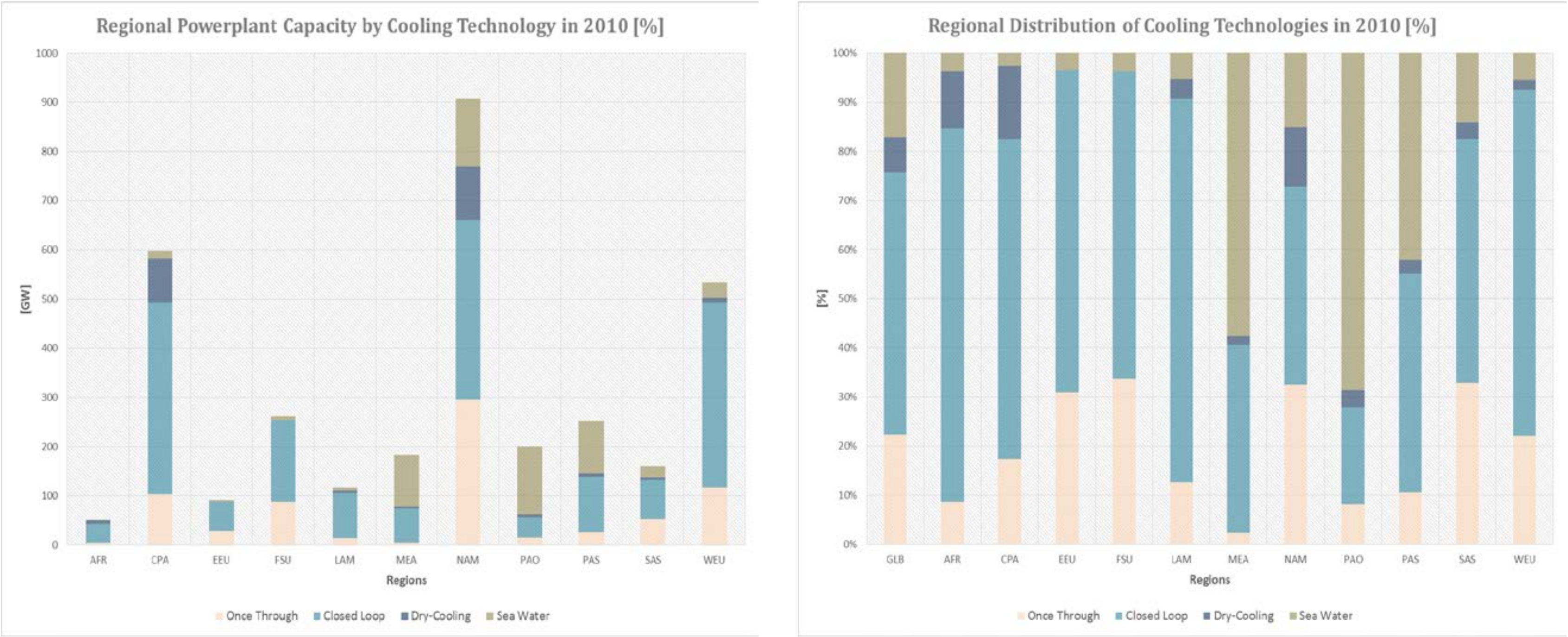

Figure S3.1 Distribution of thermoelectric generation cooling technologies in the baseline scenario explored in the analysis.

Table S3.1 Efficiency losses associated with dry cooling estimated for technologies included in the MESSAGE model. The efficiency losses are a combination of the parasitic load from fans and pumps and turbine losses. CL= closed-loop cooling, OT = once-through cooling, DC=dry cooling, SW = sea water cooling

Technology	**Power Requirements for fans and pumps [% of output]**				**Min. Turbine Losses [% of output]**		**Max. Turbine Losses [% of output]**	
	CL	**OT**	**DC**	**SW**	**CL**	**DC**	**CL**	**DC**
Coal	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
Coal CCS	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
Light oil	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
Light oil w/ combined-cycle	0.39	0.15	0.81	0.15	0.16	1.84	0.16	2.54
Gas steam turbine	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
Gas w/ combined cycle	0.39	0.15	0.81	0.15	0.16	1.84	0.16	2.54
Gas w/ combined cycle and CCS	0.39	0.15	0.81	0.15	0.16	1.84	0.16	2.54
Biomass	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
Municipal waste-to-energy	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
IGCC	0.39	0.15	0.81	0.15	0.16	1.84	0.16	2.54
IGCC w/ CCS	0.39	0.15	0.81	0.15	0.16	1.84	0.16	2.54
Nuclear	1.48	0.56	3.04	0.56	0.77	7.32	0.97	10.13
Geothermal	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03
Solar CSP	1.18	0.45	2.43	0.45	0.96	7.66	0.96	9.03

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