International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria
Email: repository@iiasa.ac.at **Telephone:** +43 (0)2236 807 342

Working paper

Balancing clean water-climate change mitigation tradeoffs

Simon Parkinson, Volker Krey, Daniel Huppmann, Taher Kahil, David McCollum, Oliver Fricko, Edward A Byers, Matthew Gidden, Beatriz Mayor, Zarrar Khan, Catherine Raptis, Narasimha D Rao, Nils Johnson, Yoshihide Wada, Ned Djilali, Keywan Riahi

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Keywan Riahi, Director, Energy Program

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Abstract

Energy systems support technical solutions fulfilling the United Nations' Sustainable Development Goal for clean water and sanitation (SDG6), with implications for future energy demands and greenhouse gas emissions. The energy sector is also a large consumer of water, making water efficiency targets ingrained in SDG6 important for long-term energy planning. Here, we apply a global integrated assessment model to quantify the cost and characteristics of infrastructure pathways balancing SDG6 clean water targets with long-term energy transformations limiting climate warming to 1.5 ˚C. The rapid expansions of water infrastructure and water efficiency to meet SDG6 targets increase energy decarbonization costs by 3 to 8 %. Conversely, under the 1.5 ˚C policy, shifts to electricity-intensive water systems in SDG6 pathways raises water prices by 2 to 9 %. Through water conservation and integrated water-energy planning we can achieve a collection of sustainability targets while avoiding incremental costs.

Acknowledgments

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Introduction

Achieving the objectives outlined in the United Nations' Sustainable Development Goals (SDG) is estimated to require annual incremental spending of 1.5 to 2.5 % of global GDP [1]. For policy-makers, the technologies and processes supplying energy and water services are of concern because the SDGs target clean water and energy for all while 2.1 billion people still lack access to an improved water source and 1.1 billion lack access to electricity [2,3]. Moreover, achieving the other SDGs, such as those related to health, ecosystems, and poverty, will be contingent on meeting water and energy sustainability objectives [4,5]. At the same time, water and energy systems are closely interlinked: water plays a key role in all stages of energy supply (e.g., fuel processing and power plant operations) [6], and conversely a significant amount of energy is required to pump and treat water resources [7]. Policy-makers aiming to achieve the SDGs are therefore eager to identify long-term infrastructure strategies that effectively balance water, energy and human development objectives in an integrated manner [8,9].

Concurrent to the SDG agenda is the UN Framework Convention on Climate Change's (UNFCCC) landmark Paris Agreement, which has the overarching objective of limiting 21st century global mean temperature change from pre-industrial levels to well below 2 ˚C while pursuing efforts to limit the temperature increase to 1.5 ˚C. Climate action is included as an SDG (SDG13), and avoiding climate change impacts is consistent with a number of the other SDGs [10]. However, there exist potential tradeoffs between deployment of certain climate change mitigation measures and solutions consistent with the SDG6 (clean water and sanitation) agenda. Specifically, increased expansion of water infrastructure in response to SDG6 targets, in particular advanced water treatment including wastewater recycling and desalination, could lead to increased energy demand and air emissions [11]. Furthermore, implementation of concentrating solar, nuclear or carbon capture and storage (CCS) technologies as emissions mitigation measures may lead to increased water use if the processes are not designed for water efficiency [12].

Despite widespread water-energy linkages, there is a lack of global-scale analysis quantifying the relative impacts of achieving SDG6 targets on the cost and characteristics of energy pathways consistent with the Paris Agreement [13]. Previous work provides important context but focused mainly on water-constrained national energy or land-use strategies in isolation [12,14-16]. Previous analysis of global development pathways incorporating multiple sustainability perspectives did not assess water access and treatment costs or interactions between SDG6 and climate change mitigation policies [17-20]. The lack of consistent policy treatment across water and energy systems at the global-scale limits our understanding of the investments needed to achieve the SDGs.

Here, we assess integrated water-energy systems transformation to begin to unravel the costs and characteristics of global pathways consistent with both the Paris Agreement and SDG6 objectives. The MESSAGEix-GLOBIOM integrated assessment model (IAM), used previously to develop globally comprehensive energy pathways consistent with deep decarbonization [21], is enhanced in this work to include a reduced-form, regionally-specific representation of the global water sector. The new approach detailed in the Methods section represents a step-change in IAM analysis because it accounts for future shifts in global water use patterns driven by a combination of socioeconomic changes and SDGs, and links these projections and policies to water availability, and the cost, energy and emissions impacts of future infrastructure systems. The coupling of water and energy policy modeling at the global-scale supports prospective analysis of the investment burden from multiple targets occurring over different sectors, timeframes and geographic scales. The analysis underscores the important role of IAMs in finding low-cost global pathways consistent with multiple SDG objectives.

Assessing integrated water-energy sustainability objectives

The Paris Agreement and SDG6 policies are mapped to criteria calculated with the enhanced IAM. The criteria settings force the IAM to identify feasible joint implementation scenarios for the 21st century in 11 geographic regions (Supplementary Information, Table 1 and Figure S1). The 1.5 ˚C climate policy is implemented as a constraint on cumulative emissions over the 21st century across energy and land systems. Consistent emission budgets and pathways are derived from previous climate model simulations [21]. The scenario for population, economic growth and other key drivers is constructed from an existing IAM representation of the middle-of-the-road Shared Socioeconomic Pathway (i.e., SSP2) [21-23].

To highlight uncertainties in the model response to policy outcomes, multiple scenarios for future water sector development are included in the analysis. Figure 1 outlines the scenarios in terms of branching points, each defining a set of scenario features reflecting a single realization of the SDG6 targets. The analysis does not cover all of the targets associated with SDG6, including targets for flood management and transboundary cooperation. Two unique pathways consistent with the SDG6 narrative bridge uncertainties driven by future end-use behavior and technological development. A supply-oriented pathway (SDG6-Supply) combines the SDG6 policy implementation with business-as-usual (baseline) water use projections. The scenario primarily features expansion of supply-side technologies in response to mitigating future demand growth. An efficiency-oriented pathway (SDG6-Efficiency) features a transition towards a future where significant progress is made on the demand-side in terms of reaching sustainable water consumption behaviour across all sectors. A key feature is the inclusion of irrigation conservation as an approach to meet water targets through re-allocation of saved water to other sectors. Recent analysis demonstrates anticipated benefits for mitigation of water stress [24].

Branching Point	Water Sector Development Scenario		
	Baseline	**SDG6-Supply**	**SDG6-Efficiency**
Water infrastructure access	1. Piped water and treatment access proceeds according to the baseline SSP2 socioeconomic projections	1. **SDG 6.1/6.2** By 2030 100% municipal withdrawals from piped water infrastructure 2. **SDG 6.2** By 2030 100% municipal return flows collected 3. **SDG 6.3/6.6** By 2030 50% of return flows treated	1. **SDG 6.1/6.2** By 2030 100% municipal withdrawals from piped water infrastructure 2. **SDG 6.2** By 2030 100% municipal return flows collected 3. **SDG 6.3/6.6** By 2030 50% of return flows treated
Water demand	1. Baseline SSP2 per capita water withdrawals and return flows	1. Baseline SSP2 per capita water withdrawals and return flows 2. **SDG 6.1** By 2030 Urban domestic withdrawals exceed 100 liters per day and rural domestic withdrawals exceed 50 liters per day	1. **SDG 6.4/6.6** Baseline SSP2 per capita water withdrawals and return flows + 10% end-use efficiency improvement due to behavior change 2. **SDG 6.1** By 2030 urban domestic withdrawals exceed 100 liters per day and rural domestic withdrawals exceed 50 liters per day
Water allocation	1. No change to allocation schemes	1. **SDG 6.4/6.6** By 2030 20 % less withdrawals from rivers and aquifers relative to 2010 2. **SDG 6.4/6.6** By 2030 minimum 5% reduction in energy sector water consumption relative to BAU	1. **SDG 6.4/6.6** Up to 30% of irrigation withdrawals can be efficiently re-allocated to other sectors. 2. **SDG 6.4/6.6** By 2030 30 % less withdrawals from rivers and aquifers relative to 2010 3. **SDG 6.4/6.6** By 2030 minimum 10% reduction in energy sector water consumption relative to BAU
Water technology development	1. Expansion of advanced recycling and desalination in water stressed regions at historical rates 2. Phase out of freshwater once-through systems 3. Energy intensive water supply technologies	1. Energy intensive water supply technologies 2. **SDG 6.4** Rapid expansion of desalination and wastewater recycling in water stressed regions 3. **SDG 6.4/6.6** No once-through power plant cooling systems (freshwater or seawater)	1. Energy efficient water supply technologies 2. **SDG 6.4** Rapid expansion of desalination and wastewater recycling in water stressed regions 3. **SDG 6.4/6.6** Increased end-use recycling by 2030 (10% reduction in consumption). 4. **SDG 6.4/6.6** No once-through power plant cooling systems (freshwater or seawater)

Figure 1: The water sector development scenarios explored in the analysis. Each scenario is made up of distinct branching points that define specific features of the embedded water-related policies and technology development narrative. Relevant SDG6 targets for specific features are indicated in bold.

The SDG6 water access and quality targets (6.1-6.3) are integrated into the IAM by constraining the required capacity of water infrastructure systems. The SDG6 pathways feature a transition in 2030 to universal piped water access and wastewater collection and towards wastewater treatment capacity able to treat a minimum of half all return flows. Increasing the fraction of wastewater that is treated also protects water-related ecosystems and is consistent with SDG6 target 6.6. In total, 3.5 billion more people require access to piped water infrastructure and wastewater collection by 2030 and 1.8 billion more people require access to wastewater treatment under the SDG6 pathway relative to the baseline scenario (Figure 2a). This result stems from the projected income-levels in 2030 under the baseline SSP2 narrative, and the associated future water source and treatment access rates derived from analysis of historical national data (Supplementary Information, Figure S2) [25]. Namely, in many low-income regions the baseline SSP2 projections do not achieve levels of water access and treatment consistent with the SDG6 targets. Some regions (e.g., Indus Basin) face multiple challenges in meeting the SDG6 objectives because of extreme water stress combined with a wide infrastructure gap projected for 2030 (Figure 2c).

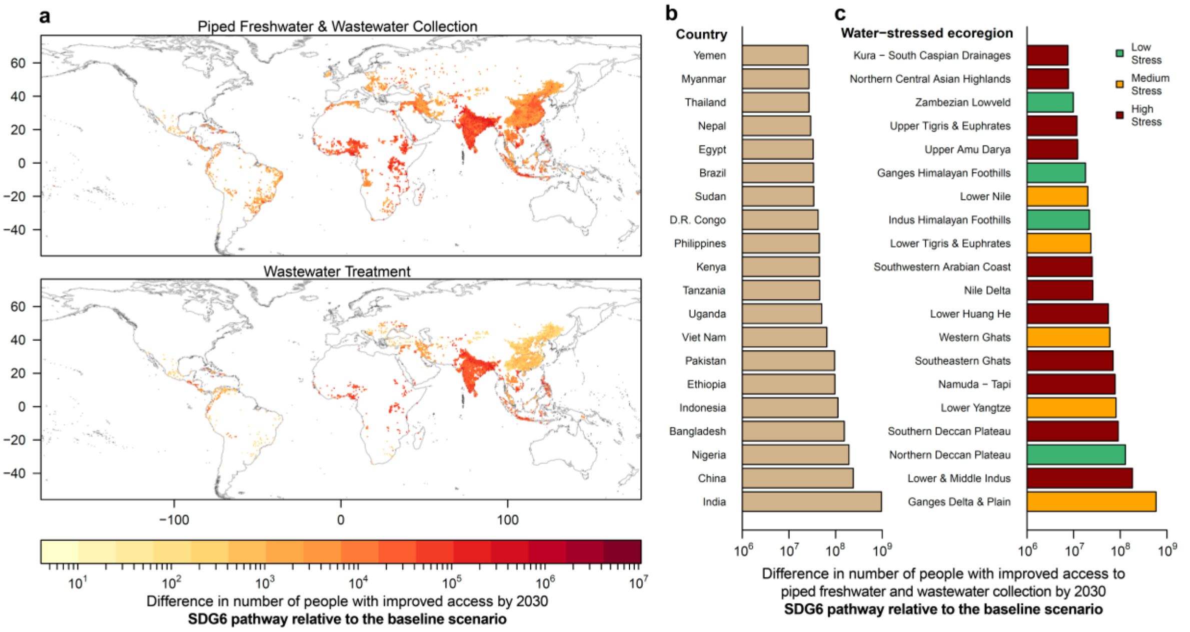

Figure 2: Comparison between projected piped water access and wastewater treatment rates under the SDG6 and baseline water policy scenarios a. Spatially-explicit (7.5 arc-minutes) differences between projected piped water access and water treatment levels in the SDG6 scenario relative to the baseline scenario; b. differences in population with piped water access and wastewater collection aggregated by country [26]; and c. differences categorized by the water-stressed ecological regions defined in Hoekstra et al. (2010) [27] (Supplementary Information, Figure S4).

Consistent water withdrawal and return flow trajectories for the SSP2 scenario are generated to represent demands in the irrigation, municipal (domestic) and manufacturing sectors (see Methods). To reflect transformation towards universal access to sufficient water for human development, municipal water withdrawals in all countries in the SDG6 pathways are adjusted such that all urban areas achieve per capita demands of at least 100 liters per day while rural areas achieve demands of at least 50 liters per day (Supplementary Information, Figure S3) [28-30]. Costs for water distribution and wastewater collection in the municipal and manufacturing sectors are estimated based on the modeled withdrawal and return-flow volumes. Expansion pathways for advanced water treatment (i.e., wastewater recycling and desalination) are incorporated into the water sector transformations to supply increasing future urban withdrawals in water stressed regions [31-33], which is in line with SDG6 target 6.4 (substantially reduce the number of people suffering from water scarcity). Diffusion is limited based on an analysis of historical expansion rates and national GDP trajectories. Wastewater recycling is prioritized over desalination in all locations to reflect additional sustainability challenges associated with desalination. Wastewater recycling can take various forms, including direct application of domestic wastewater for uses that do not require potable quality [34]. To assess impacts on the results we incorporate a transition towards low-cost, energy-efficient recycling systems in the SDG6-Efficiency scenario using performance data identified in the literature (Supplementary Information, Table S3).

Average conservation costs and anticipated demand responses to increasing water supply costs are included in the assessment of infrastructure options using conservation supply curves (Supplementary Information, Figure S7). The curves enable conservation of a fixed percentage of the baseline water withdrawals and return-flows in each sector. Water efficiency measures aligned with SDG6 target 6.4 are also embedded into the SDG6 energy transformation pathways. Energy sector water consumption post-2030 is limited to a fixed percentage of the estimated freshwater consumption in the baseline scenario without climate policy (5 % less in the SDG6-Supply scenario and 10 % less in the SDG6-Efficiency scenario). This pushes the energy sector in each region to improve water consumption intensity through transformational changes in the energy supply-chain. Furthermore, once-through cooling systems are phased-out completely in the SDG6 scenarios helping to protect water-related ecosystems in line with SDG6 target 6.6. The manufacturing sector is also assumed to implement water conservation measures more aggressively in the SDG6-Efficiency pathways, achieving per capita water intensities that align with a sustainable consumption narrative. The withdrawal and return flow trajectories for each region including the impacts of conservation are presented in the Supplementary Information (Figures S8-S12).

Transformation pathways and policy integration costs

Select global indicators calculated with the enhanced IAM under the water sector development scenarios are depicted in Figure 3. In both SDG6 scenarios, global freshwater withdrawals from rivers and aquifers and untreated return flows decrease relative to the estimated 2010 volumes (Figure 3a). In the SDG6-Efficiency scenario, 26 % less freshwater is withdrawn from rivers and aquifers and 43 % less wastewater is returned to the environment untreated by 2030 relative to volumes estimated for 2010. The conservation would improve environmental flows in some regions while reducing water pollution, although quantification of the benefits requires further analysis with biophysical models.

To avoid freshwater withdrawals from conventional surface and groundwater resources while increasing the fraction of wastewater that is treated, an upscaling of efficiency, alternative freshwater sources and wastewater treatment capacity is required. In the SDG6-Supply scenario, global water sector electricity consumption (Figure 3d) increases from 815 TWh in 2010 to more than 2000 TWh by 2070, reflecting growing water demands and expanded use of advanced water treatment (wastewater recycling and desalination). In contrast, electricity consumption for water supply decreases in the SDG6-Efficiency scenario due to lower water demands and higher energy efficiencies assumed for the water technologies.

Global carbon emissions in 2030 (Figure 3c) do not vary signficantly across scenarios (< 2 %) indicating minimal interactions between climate policy and the ramp-up in electricity-intensive water infrastructure systems to meet the SDG timeline. Emissions in the 1.5 ˚C scenarios reduce rapidly and are negative in 2070. Global energy sector water consumption (Figure 3e) is at the same time increasing in all scenarios. The baseline 1.5 ˚C energy transformation pathway requires more water than when no climate policy is included for two reasons: 1) there are higher electricity demands from increasing end-use electrification; and 2) certain low-carbon power generation options have a larger water footprint than conventional combined-cycle natural gas systems prevalent in transformations under no climate policy. The SDG6 scenarios feature additional water efficiency targets that achieve net reductions compared to estimated 2010 levels, but the conserved water volumes are paltry when considered in the broader context of the volumes supporting irrigation, municipal and industrial sectors (Figure 3a).

Overall impacts of the transformations on the undiscounted costs for water and energy systems (Figure 3f) indicate annual spending needs to be increased between 92 and 125 % by 2030 in order to achieve the clean water targets while placing infrastructure on a path consistent with 1.5 ˚C. Comparing results across scenarios further indicates that to 2030, similar effort is needed to move towards pathways consistent with SDG6 as with 1.5 ˚C, but that in the long-term, investments to achieve 1.5 ˚C dominate. The sustainable consumption narrative embedded in the SDG6-Efficiency scenario results in the long-term costs decreasing relative to the other scenarios tested due to avoided spending on water infrastructure. It is important to emphasize that broader impacts of the SDG6-Efficiency narrative on e.g., production costs in the manufacturing sector are not accounted for in the presented cost estimates, which could impact the anticipated benefits of water conservation.

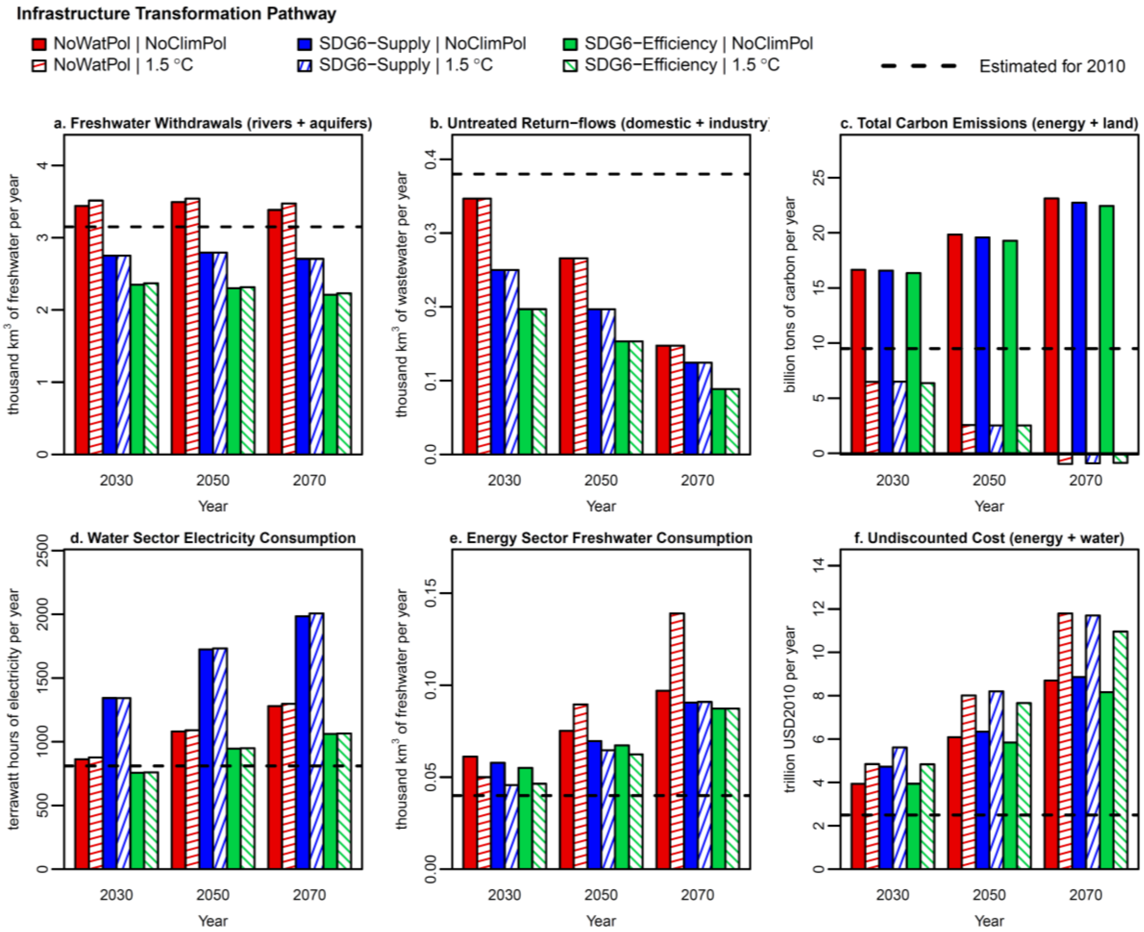

Figure 3: Impacts of combined water and climate policies on select global sustainability indicators: a. Freshwater withdrawals from rivers and aquifers across irrigation, municipal and industrial sectors; b. Untreated return-flows from the municipal and industrial sectors; c. Total carbon emissions across energy and land systems; d. Water sector energy consumption (electricity); e. Energy sector water consumption (excluding hydropower); and f. Undiscounted costs calculated across water and energy systems (sum of the investment, fixed and variable cost components).

Impacts of the combined policies on infrastructure costs in 2030 and 2070 for the water and power sectors are summarized in Figure 4, with further results for each region detailed in the Supplementary Information (Figure S16-S21). The water sector costs (Figure 4a) are dominated by distribution (pumping) and sewerage infrastructure, especially in low-income regions such as Sub-Saharan Africa where a massive upscaling compared to baseline levels is required. In the SDG6-Supply scenarios, global desalination capacity expands from an estimated 24 km^3 in 2010 to 253 km^3 in 2070, while advanced wastewater recycling capacity expands from an estimated 16 km^3 in 2010 to 717 km^3 in 2070 (Supplementary Information, Figures S18 and S19). Spending on advanced water treatment reaches 580 billion USD per year by 2070 in the SDG6-Supply scenario (Figure 4a). Conversely, the avoided water withdrawals and return-flows in the SDG6-Efficiency pathways leads to reduced spending on advanced water treatment infrastructure in 2070 with total costs of 169 billion USD. Estimated conservation spending is at the same time increasing from 100 billion USD in the SDG6-Supply pathways by 2070 to more than 300 billion USD in the SDG6-Efficiency scenarios.

Average annual costs are 2 to 3 times higher in the power sector when compared to the water sector (Figure 4b), but this gap varies widely across regions (Figure 4c). Power sector costs in 2030 and 2070 in all scenarios are dominated by natural gas systems, despite a rapid transition towards power supply dominated by low-carbon generation in the 1.5 °C scenarios (Supplementary Information, Figure S21). This result stems from the operational costs estimated for natural gas systems, which is increasing rapidly under a 1.5 °C policy due to endogenous emission pricing. Electricity supply is also approximately 40 % higher by 2070 in the 1.5 °C pathways due to increased end-use electrification.

Power sector capacity is needed to cover electricity-intensive water infrastructure in the SDG6-Supply scenarios (2000 TWh per year by 2070 or 40 % greater than in the SDG6-Efficiency scenario). There is also reduced investment into nuclear systems, and increased expansion of wind and solar PV technologies in both SDG6 scenarios due to favourable water efficiency outcomes.

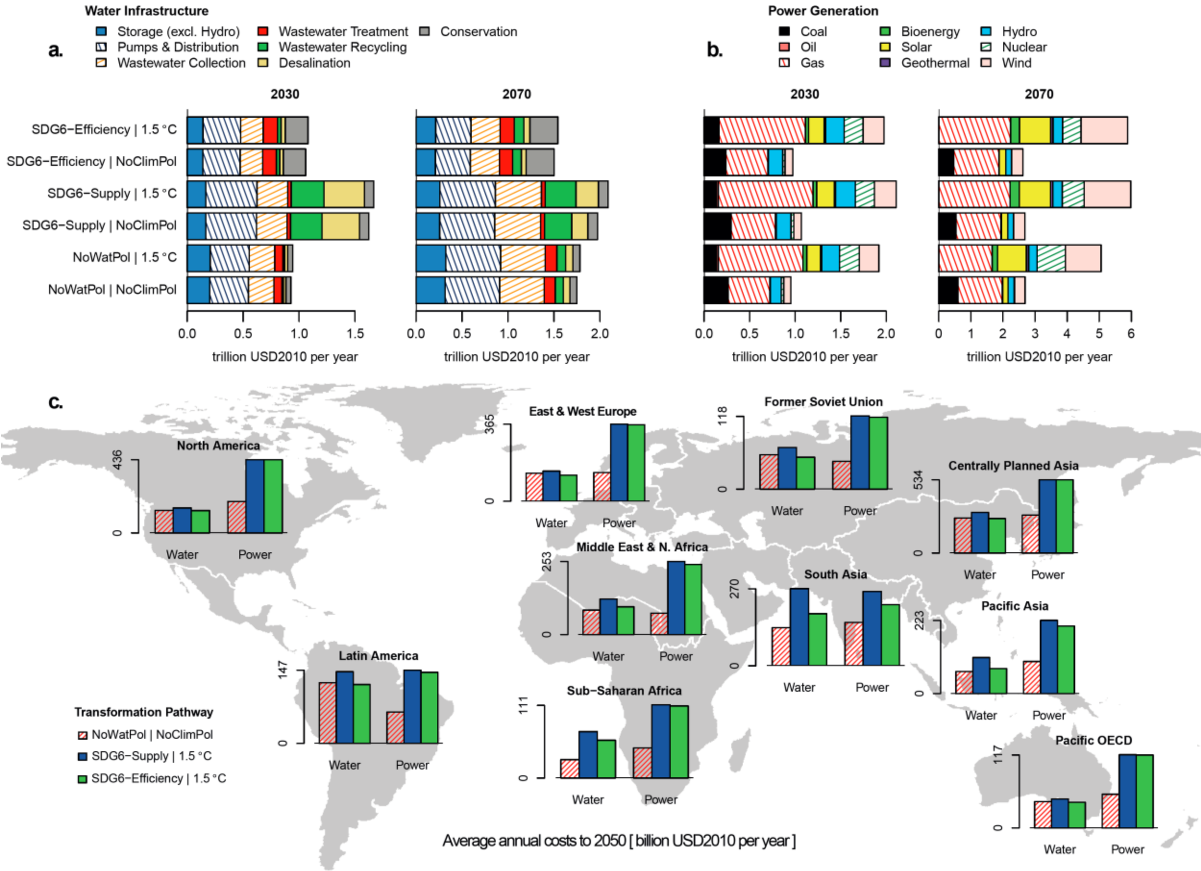

Figure 4: Evolution of global infrastructure costs to support combined water-climate policy objectives. Costs are computed as the sum of the investment, fixed and operational components. a. global water infrastructure costs in 2030 and 2070; b. global power generation costs in 2030 and 2070; and c. average annual water infrastructure and power generation costs by region to 2050. A full list of countries included in each region is provided in the Supplementary Information (Table S1).

Increasing costs in the power sector are translated to water infrastructure systems according to the intensity of water sector electricity consumption, which is increasing in the SDG6 pathways. Urban water price trajectories obtained from the supply-demand balance on urban freshwater withdrawals are depicted in Figure 5a. The maximum price trajectory tracks water prices in regions facing the greatest challenges in terms of water stress, population growth, and existing infrastructure coverage (e.g., South Asia), and the trajectories peak initially in 2030 reflecting efforts needed to ramp up infrastructure spending to meet the SDG timeline. The price trajectories across climate policy settings in the SDG6-Supply pathways differ as a result of increasing electricity prices and electricity intensity of water supply. Figure 5b depicts estimated future spending on electricity in the water sector across scenarios, and indicates that combining the 1.5 ˚C policy with the SDG6-Supply scenario increases electricity spending to 112 billion USD in 2030 and to 163 billion USD in 2070. Conversely, spending remains relatively steady in the SDG6-Efficiency scenario, reaching a much lower global expenditure of 108 billion USD by 2070, and this is due again to the embedded sustainable consumption narrative combined with the transition towards more energy-efficient water supply technologies. A similar scale of spending will be needed to simultaneously transition power systems towards more water efficient cooling technologies (Figure 5c), which are more expensive and less energy-efficient than conventional options and becoming increasingly expensive to operate under decarbonization. More stringent water efficiency targets in the SDG6-Efficiency scenario requires less spending than in the SDG6-Supply scenario because of lower water supply prices under increased end-use conservation.

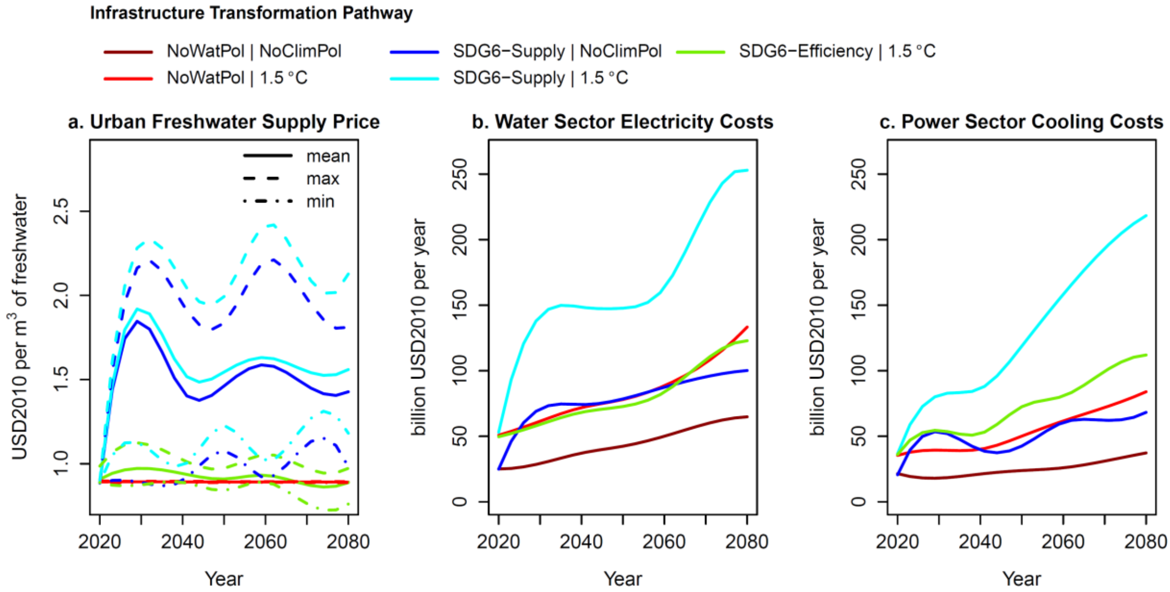

Figure 5: Impacts of the combined SDG6 and 1.5 °C policies on future water-related costs: a. Urban water freshwater supply price distributions across the 11 geographic regions; b. global water sector electricity costs; and c. global costs for investing and operating cooling technologies in the power sector. Annual changes are interpolated using the decadal results from the IAM.

Limitations

Bioenergy (sourced from rain-fed feedstocks) and hydropower continues to play an important role in the modeled SDG6 electricity pathways. This occurs because precipitation lost during bioenergy feedstock cultivation and reservoir storage are not incorporated into the SDG6 water efficiency targets. Significant uncertainty surrounds these components of the freshwater balance and the impacts on water sustainability [35,36]. Adjusting coverage of the implemented policies to include additional precipitation consumption would limit expansion of hydropower and bioenergy in the modeled pathways, creating additional costs in regions featuring expansion of hydropower and bioenergy in response to climate policy (e.g., Latin America). The analysis also did not consider impacts of interbasin transfers, future flood management, transboundary agreements, fertilizer application or livestock waste management practices in response to water targets, which would present further constraints to the development pathways. More spatial detail is also needed to unravel within-basin impacts of upstream conservation on downstream water availability. Finally the analysis in this paper does not cast a wide enough net to capture the expected benefits of climate change mitigation in terms of the avoided impacts on water resources and consequently the performance of energy technologies that rely on water availability. Significant geographic diversity is anticipated, and impacts may be partially mitigated when aggregated across regions and globally [37,38]. Nonetheless, avoiding adaptation costs in the 1.5 °C scenarios is expected to improve synergies with the SDG6 targets in many regions. These uncertainties and linkages to other SDG6 indicators will be assessed in future research.

Discussion

This paper quantified interactions between specific SDG6 targets and the Paris Agreement objective of limiting global warming to 1.5 °C. We find that implementation of the SDG6 targets for water access and wastewater treatment cause relatively minor impacts to electricity sector costs when compared to the effort needed for climate change mitigation. At a global-scale, average annual electricity sector costs increase in 2030 between 3 and 8 \% when the SDG6 policies are added on top of a 1.5 °C climate policy. We also find that water efficiency targets aligned with SDG6 applied to the energy sector could cause fundamental shifts in the long-term energy technology strategy used to mitigate climate change. Specifically, there is increased exploitation of wind and solar technologies as well as use of air cooling systems to simultaneously reduce carbon and water intensity of electricity. Incremental implementation costs could overshadow impacts of expanding water systems on future energy demands. Our results further demonstrate that climate change mitigation will impact water prices, and that effects will be greatest in regions facing rapid socioeconomic change and existing water stress. At a regional-scale, municipal water prices are between 2 and 9 % higher when the 1.5 ˚C target is added on top of the SDG6 policies. Major cost uncertainties relate to the scale of future water demand growth in water stressed regions and how re-allocation across sectors can address supply expansion. We find that a transition to achievable water consumption intensities combined with re-allocation of water across sectors can largely offset tradeoffs between the investigated SDG6 targets and climate policy.

Finding and improving synergies between decarbonization and water efficiency is therefore paramount for minimizing joint policy implementation costs and uncertainties. For example, many processes within the water sector are ideal candidates for recruitment in electricity sector demand response programs or for integration with combined heat and power management [39,40]. Leveraging these solutions will be important for increasing energy efficiency and the penetration of renewable generation sources. Moreover, continuing innovation with emerging wastewater treatment processes could lead to significant reductions in energy requirements [41]. In the near term, water and energy resource planners should promote integrated valuation of efficiency measures and supply-side projects to ensure system development aligns with sustainability goals [42].

To our knowledge, this paper is the first to provide harmonized global pathways for water and energy infrastructure that align with elements of SDG6 and a 1.5 ˚C climate target. Future research must address additional SDG6-climate change mitigation challenges involving floods, stormwater infrastructure, transboundary agreements, and climate change adaptation by zooming into local areas to assess the multi-sector costs and benefits of policy integration [43]. In this context, it is critical to incorporate clean water-climate change mitigation interactions with other SDGs, particularly those with strong interdependencies, such as the SDGs involving targets for poverty, food, health and biodiversity.

Methods

MESSAGEix-GLOBIOM integrated assessment model

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a linear programming (LP) energy engineering model with global coverage [17,44]. As a systems engineering optimization model, MESSAGE is primarily used for medium- to long-term energy system planning, energy policy analysis, and scenario development. The model provides a framework for representing an energy system with all its 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. To assess economic implications and to capture economic feedbacks of climate and energy policies, MESSAGE is linked to the aggregated macro-economic model MACRO [45].

The version of MESSAGE utilized in this paper is part of the borader MESSAGEix-GLOBIOM integrated assessment framework. MESSAGEix-GLOBIOM 1.0 integrates the energy engineering model MESSAGE with the land-use model GLOBIOM (GLobal BIOsphere Management) via soft-linkage into a global integrated assessment modeling framework [21,23,46]. The soft-linkage is realized with a reduced form emulator of GLOBIOM land-use pathways [21]. GLOBIOM is a partial equilibrium model that represents the competition between different land-use based activities [47,48]. It includes a detailed representation of the agricultural, forestry and bio-energy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, including comprehensive AFOLU (agriculture, forestry and other land use) GHG emission accounts and irrigation water use.

MESSAGEix-GLOBIOM covers all greenhouse gas (GHG)-emitting sectors, including energy, industrial processes as well as agriculture and forestry. The emissions of the full basket of greenhouse gases including CO2, CH4, N2O and F-gases (CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF6) as well as other radiatively active substances, such as NOx, volatile organic compounds (VOCs), CO, SO2, and BC/OC are represented in the model. MESSAGEix-GLOBIOM is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6.8 [49] for calculating atmospheric concentrations, radiative forcing, and annual-mean global surface air temperature increase. This provides a consistent framework for estimating global emission budgets associated with international climate policies, which are often stated in terms of global mean temperature change (e.g., 1.5 or 2 °C) [50].

The version of MESSAGEix-GLOBIOM utilized in this paper and associated data is parameterized following the most recent global socioeconomic scenarios, the Shared Socioeconomic Pathways (SSPs), and is detailed in Fricko et al. (2017) [21]. This version of the IAM represents the world as eleven regions (Supplementary Information, Figure S1 and Table S1) in an attempt to represent the global energy system in a simplified way, with trade flows (imports and exports) between regions included in the decision variables. Additional constraints in the model scenarios ensure universal energy access, prevent bioenergy from being sourced from irrigated crops [17], and limit the carbon price of land-based mitigation measures to avoid impacts to food pricing in low-income regions.

Energy sector water use

The water withdrawal and return flows from energy technologies are calculated in the version of MESSAGE utilized in this study following the approach described in Fricko et al. (2016) [6] Each technology is prescribed a water withdrawal and consumption intensity (e.g., m^3 per kWh) that translates technology outputs optimized in MESSAGE into water requirements and return flows. For power plant cooling technologies, the amount of water required and energy dissipated to water bodies as heat is linked to the parameterized power plant fuel conversion efficiency (heat-rate). This enables the fuel efficiency improvements included in MESSAGE to be translated into improvements in water intensity. Water withdrawal and consumption intensities for power plant cooling technologies in the version of MESSAGE utilized in this paper are calibrated to the range reported in Meldrum et al. (2013) [51]. Additional parasitic electricity demands from recirculating and dry cooling technologies are accounted for explicitly in the electricity balance calculation. All other technologies (other than hydropower generation) follow the data reported in Fricko et al. (2016) [6].

A key feature of the implementation in this paper is the optimization of power plant cooling technology options for individual power plant types (Supplementary Information, Figure S14). Each power plant type that requires cooling in MESSAGE (e.g., natural gas combined-cycle power plant) is connected to a corresponding cooling technology option (once-through, recirculating or air cooling), with the investment into and operation of the cooling technologies included in the optimization decision variables. This enables MESSAGE to choose the type of cooling technology for each power plant type and track how the operation of the cooling technologies impact water withdrawals, return flows, thermal pollution and parasitic electricity use. Costs and efficiency for cooling technologies are estimated following previous technology assessments (Supplementary Information, Table S2) [52-54]. The initial distribution of cooling technologies in each region and for each technology is estimated with the dataset described in Raptis and Pfister (2016) [55]. Specifically, the share of each type of cooling technology (once-through, recirculating or air cooling) is estimated in each region by mapping the technology classification in MESSAGE onto that in the Raptis and Pfister dataset. Technologies without data are assumed to follow regional average cooling technology shares taken across all power plant types (Supplementary Information, Figure S13). It is assumed that once-through cooling technologies are phased-out with the retirement of existing power plants due to the increasing cost competitiveness of recirculating systems [54], benefits to system security [56], and existing national trends [57,58].

Water supply sector

A reduced-form freshwater balance and water infrastructure investment module is incorporated into the version of MESSAGE described previously to enable quantification of key interactions between water and energy systems under sustainability transitions (Supplementary Information, Figure S15). Freshwater withdrawals from different sectors are balanced with supplies in each model decision-making period t and region n:

$$F_{n,t} + R_{n,t} + D_{n,t} = \sum_{s} (W_{s,n,t} - C_{s,n,t}) \quad (1)$$

where F is the freshwater supplied from rivers and aquifers, R is the freshwater supplied from wastewater recycling facilities, D is the freshwater supplied from desalination facilities, W is the baseline withdrawal from sector s (agriculture, municipal, manufacturing and energy), and C is the water conserved through implementation of conservation measures. Freshwater supply is constrained by renewable water availability V, which in this paper is defined as a fraction of the base-year (2010) withdrawals to enable interactive implementation of long-term conservation targets using existing water stress indicators:

$$F_{n,t} \leq V_{n,t} = (1 - \varphi_t) \cdot F_n^0 \quad (2)$$

where F^0 is the base-year freshwater withdrawals from rivers and aquifers, and φ is the fraction of base-year withdrawals to be conserved. The conservation fraction is set based on the water sector development narrative (Figure 1) combined with an assessment of future demands and degree of water stress at the river basin-scale. The degree of water stress (i.e., low, medium, and high) is defined relative to the calculated ratio between historical withdrawals and renewable water availability (i.e., F^0/V), and is estimated previously for global basin regions with modeled runoff data from the WaterGAP global hydrological model [27,59]. The assessment does not consider intra-annual variability and long-term shifts in water stress driven by climate change. Water availability might alternatively be defined as in Kim et al., (2016), i.e., relative to estimated basin-scale base-flow metrics calculated with a global hydrological model [19].

Exogenous projections of aggregate regional agriculture, municipal and manufacturing water use define the baseline withdrawals in equation (1). Irrigation is the only component of agricultural sector withdrawal considered in this work, and is defined according to the results from GLOBIOM described previously. Irrigation return flows are excluded because of difficulties capturing these flows for re-use and treatment. The municipal water use modeling approach generates projections for both urban and rural components of municipal withdrawals and return-flows based on projections of population and income-level [60]. Gridded urban population and GDP projections from Jones and O'Neill (2016) and Gidden et al. (forthcoming) are used to parameterize consistent socioeconomic inputs at 7.5 arc-minutes [61,62]. Manufacturing demands are generated following a similar approach as in Hejazi et al. (2014) [63]. Namely, historical country-level data for 2010 is estimated by subtracting energy sector withdrawals calculated with MESSAGE for 2010 from total industrial sector (i.e., manufacturing and energy) withdrawals reported at the country-level in Floerke et al. (2013) [64]. Future changes in manufacturing demands are projected assuming convergence towards a log-linear model between GDP and manufacturing withdrawals compiled for 2010. Water efficiencies leading to lower manufacturing withdrawals and consumption levels are assumed to follow the estimated municipal sector improvements [60]. The demands are distributed across countries based on growth in GDP, and then downscaled to 7.5 arc-minutes using the gridded urban population projections from Jones and O'Neill (2016) [61].

Many people still lack access to an improved water source and wastewater treatment, and the water use of these individuals is modeled to include relevant SDG6 indicators and the costs of distribution infrastructure. It is assumed that any withdrawal or return flow from population remaining without access to an improved water source (urban or rural) is met by conventional surface water resources and without wastewater treatment. Projections of the population connected to an improved water source and those with both an improved water source and wastewater treatment are initially generated using a logistics model fit to historical country-level data for 2010 from Baum et al. (2013) [25], and per capita income data aligned with the SSPs from Dellink et al. (2017) [65] (Supplementary Information, Figure S2). National values are downscaled to 7.5 arc minutes using consistent economic activity projections for the SSPs from Gidden et al. (forthcoming) [62].

Infrastructure required to distribute potable freshwater and to collect wastewater is an important component of water supply costs. A simplified representation of this infrastructure is incorporated into MESSAGE using the estimated connection rates and withdrawal volumes. The capacity of piping and pumps in distribution/collection systems varies with the maximum withdrawal rates. We adopt average per capita costs for the development of piped water and wastewater collection reported by the World Health Organization [66-68], and convert to per volume costs using a decent living daily recommendation of 100 liters per day for urban areas and 50 liters per day in rural areas (Supplementary Information, Figure S3) [28-30]. Vintaging of the piped water and wastewater collection infrastructure in MESSAGE is estimated by simulating the build-up of capacity in historical years according to the historical national withdrawals and return-flows in Floerke et al. (2013) [64] and the estimated connection rates, calculated using the logistics model fit previously to back-cast historical connection levels based on historical GDP.

Conservation cost curves are defined for additional end-use water conservation measures in the municipal, manufacturing and agricultural sectors. Significant diversity in conservation measures exists across regions, and a full assessment of the opportunities and implementation costs is beyond the scope of this paper. We alternatively applied a stylized approach to include expected conservation costs and impacts at the regional-scale. Previous work quantified the impact of various conservation options and associated implementation costs, and generally show that conservation costs increase non-linearly and offset a limited fraction of water demand [69-72]. We assume a general form for the conservation curve that enables consistent linearization across regions (Supplementary Information, Figure S7). A maximum conservation potential in each sector representing 30 \% of the baseline withdrawals is assumed in this study, and is a somewhat conservative interpretation of previous assessments that focus specifically on water conservation potentials for specific sectors [69,70,72,73]. We use 0.3 USD per m3 to represent the average cost for conservation measures because this approximates the point at which it can be expected that investment switches to expanding yield from conventional raw surface and groundwater sources [74].

A representation of expected reservoir costs are also included in the accounting for freshwater withdrawals using the average investment cost parameters for mid-sized systems compiled in Keller et al. (2000) [75]. Reservoir storage-yield relationships are complex and depend on time horizon and management strategy [76], and for simplicity reservoir capacity is sized to meet the total freshwater withdrawals from rivers and aquifers assuming a one-to-one relationship (i.e., each m^3 per year of freshwater withdrawn from rivers and aquifers is supported by an equivalent amount of reservoir storage). Historical capacities and vintaging is calibrated to match the historical withdrawal data presented in Floerke et al. (2013) [64]. We assume a lifetime of 80 years for the water supply reservoirs, and emphasize that the formulation does not incorporate impacts of sedimentation on reservoir performance, which would require further investment to correct, but can also be minimized in future reservoir design [77].

A 150 km buffer around the global coastline is used to identify potential future withdrawals in water stressed regions suitable for seawater desalination. The buffer width reflects the additional costs and energy use associated with the seawater conveyance infrastructure and the relative likelihood of finding alternative local water supplies (e.g., wastewater recycling, brackish groundwater, etc.) at lower cost and energy intensity [32]. Population outside the 150 km buffer that reside in water-stressed regions are also assumed to transition towards increased use of advanced wastewater recycling technologies that upgrade municipal and manufacturing return flows to potable standards. Lower bounds for desalinated and recycled water supply in each grid cell are subsequently derived by combining the geographical categorization described above with estimates of the market penetration and the projected total urban withdrawals (aggregate of urban municipal and manufacturing demands). Similar to Caldera et al. (2016) [33], the market penetration of advanced water treatment technology is initially limited based on degree of water stress: it is assumed that a minimum of 25\% of the total urban withdrawal volumes should be met using recycling and/or desalination in all grid-cells classified as having a low-level of water stress, a minimum of 50\% in grid-cells classified as having a medium stress-level, and a minimum of 75\% in grid-cells classified as having a high stress-level. For desalination, the grid-cell must also be within 150 km of the coast, as described above (Supplementary Information, Figure S6).

The diffusion of desalination and recycling is further constrained along a defined path to reflect lack of access to capital for investing in advanced water treatment technology in low-income regions. The diffusion is limited using a symmetric logistic growth model that saturates at a per capita GDP equivalent to Israel in 2010 (approximately 30,000 USD). Israel is selected as the baseline because it hosts significant desalination and wastewater recycling capacity (e.g., approximately 80 % of urban wastewater is recycled), and has plans to significantly expand on this infrastructure in the coming decades [78]. Technology diffusion is also limited by a host of other factors that are difficult to model, such as planning procedures, materials availability and local experience. To reflect these challenges in a simplified way we further limit growth of desalination and recycling technologies to less than 5 % a year, which lies within recent expansion rates calculated with a global desalination database [32] (Supplementary Information, Figure S5). A maximum recycling rate of 80\% of the urban return flow is assumed to reflect difficulties in capturing and recycling all wastewater to potable standards. The penetration of desalination or recycling is multiplied by the estimated connection rate and treatment rates where applicable to arrive at the fraction of total urban withdrawal supplied from wastewater recycling and desalination in each grid cell. The gridded data are aggregated into the corresponding MESSAGE regions to define a minimum level of advanced water treatment capacity in each region and time-step:

$$R_{n,t} \geq \sum_{i \in I_n \cap S} \gamma_{i,t} \cdot \beta_{i,t} \cdot r_{i,t} \tag{3}$$

$$D_{n,t} \geq \sum_{i \in I_n \cap S \cap K} \left[\pi_{i,t} \cdot \left(\alpha_{i,t} \cdot w_{i,t} - \varepsilon_{i,t} \cdot \gamma_{i,t} \cdot \beta_{i,t} \cdot r_{i,t} \right) \right] \tag{4}$$

where *i* denotes a specific grid-cell in the 7.5 arc-minute global population map, I is the complete set of populated grid-cells in a specific MESSAGE region, S is the complete set of grid-cells in water-stressed regions, K is the complete set of grid-cells in the 150 km coastline buffer, w is the urban withdrawal (municipal plus manufacturing), r is the urban return flow, α is the fraction of demand connected to an improved source, β is the fraction of return-flow connected to treatment, γ is the penetration of wastewater recycling, and π is the penetration of seawater desalination. It is important to emphasize that the constraints above represent lower bounds and that additional desalination and recycling can be expanded in scenarios to address additional freshwater availability constraints applied in equation (2).

Thermal and membrane desalination technologies are distinguished in MESSAGE (Supplementary Information, Table S3). Existing seawater desalination capacities are identified by analyzing global facility-level data provided in the desal database and refined in Hanasaki et al. (2016) [32] (Supplementary Information, Figure S5). Some facilities are missed in the database, and the existing capacities are calibrated such that the global installed capacity aligns with reported estimates in 2010 of approximately 25 km^3 per year [79]. Average cost and performance metrics for desalination are estimated based on data found in the literature [80,81]. For the investment cost projections, we assume improvements in line with the logistic technological learning model presented in Mayor (2018) [82].

Multiple wastewater treatment technologies are also distinguished in MESSAGE (Supplementary Information, Table S3). There exists a wide variety of wastewater treatment methods and technologies, and to simplify the number of decision variables in MESSAGE, two generalized urban wastewater treatment technologies are defined. The first technology represents a standard secondary-level treatment facility found in a mid-sized city [83,84]. The other technology provides wastewater recycling capabilities, and is parameterized to represent a standard facility found in a mid-sized city that is suitable for upgrading municipal or manufacturing wastewater to potable standards (e.g., a membrane bioreactor) [83,84]. A further rural wastewater treatment technology is defined to represent infrastructure satisfying the United Nation's guidelines for clean water and sanitation in rural areas, and is equivalent to a common septic system [67]. There should be enough wastewater treatment capacity, consisting of both recycling and conventional treatment activities, to ensure there is sufficient build-out to support the projected return-flow connected to treatment. Using the estimated recycling penetration, the inflow to conventional treatment facilities P is defined as follows:

$$P_{n,t} \geq \sum_{i \in I_n} \left[\left(1 - \gamma_{i,t}\right) \cdot \beta_{i,t} \cdot r_{i,t} \right] \quad (5)$$

A facility level database for existing wastewater treatment infrastructure with global scope, to our knowledge, does not exist [85,86], and alternatively existing capacities in each region are estimated based on the logistics model derived previously and the country-level data compiled in Baum et al. (2013) [25], which describes the percent of a country's population with access to wastewater treatment. The fraction with access to treatment in 2010 is multiplied by the total return flow in 2010 to estimate the capacity of wastewater treatment facilities. Limited national data from AQUASTAT is used to estimate existing wastewater recycling capacities. Vintaging of the wastewater technologies in MESSAGE is estimated by simulating the build-up of capacity in historical years according to the historical national return-flows in Floerke et al. (2013) [64] and the estimated treatment penetration, calculated using the logistic model fit previously to back-cast historical treatment levels based on historical GDP. Investment cost improvements for wastewater recycling are assumed to follow desalination.

Average energy intensities (e.g., kWh/m^3) are assumed for the water technologies, and are defined using data obtained from previous technology performance reviews (Supplementary Information, Table S3) [81,84]. We do not consider energy used during construction and disposal of the water infrastructure, but note that these components of energy use are typically a small fraction compared to the operational energy requirements [87]. The energy use is accounted for in the energy supply projections, hard-linking the water and energy sectors in the optimization framework. The initial energy demands from MESSAGE are top-down projections meant to include the water sector, and so are calibrated using the estimated historical water infrastructure capacities and assumed energy intensities.

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Supplementary Information

Balancing clean water-climate change mitigation tradeoffs

Simon Parkinson[1,2], Volker Krey[1], Daniel Huppmann[1], Taher Kahil[1], David McCollum[1,3], Oliver Fricko[1], Edward A Byers[1], Matthew Gidden[1], Beatriz Mayor[1], Zarrar Khan[1,4], Catherine Raptis[5], Narasimha D Rao[1], Nils Johnson[1], Yoshihide Wada[1,6], Ned Djilali[2], Keywan Riahi[1,7,8]

[1] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria
[2] University of Victoria, PO Box 3055 STN CSC, V8W 3P6 Victoria BC, Canada
[3] University of Tennessee,1640 Cumberland Avenue, 37996-3340 Knoxville TN, United States
[4] Universidad Pontificia Comillas, Calle de Santa Cruz de Marcenado 26, 28015 Madrid, Spain
[5] ETH Zurich, John-von-Neumann-Weg 9, 8093 Zurich, Switzerland
[6] Utrecht University, PO Box 80.115, 3508 Utrecht, The Netherlands
[7] TU Graz, Inffeldgasse 21, 8010 Graz, Austria
[8] Colorado School of Mines, 1500 Illinois Street, Golden, CO 80401, USA

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Corresponding Author: S. Parkinson (parkinso@iiasa.ac.at)

Table S1 Countries included in the MESSAGE macro-regions.

Region	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, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

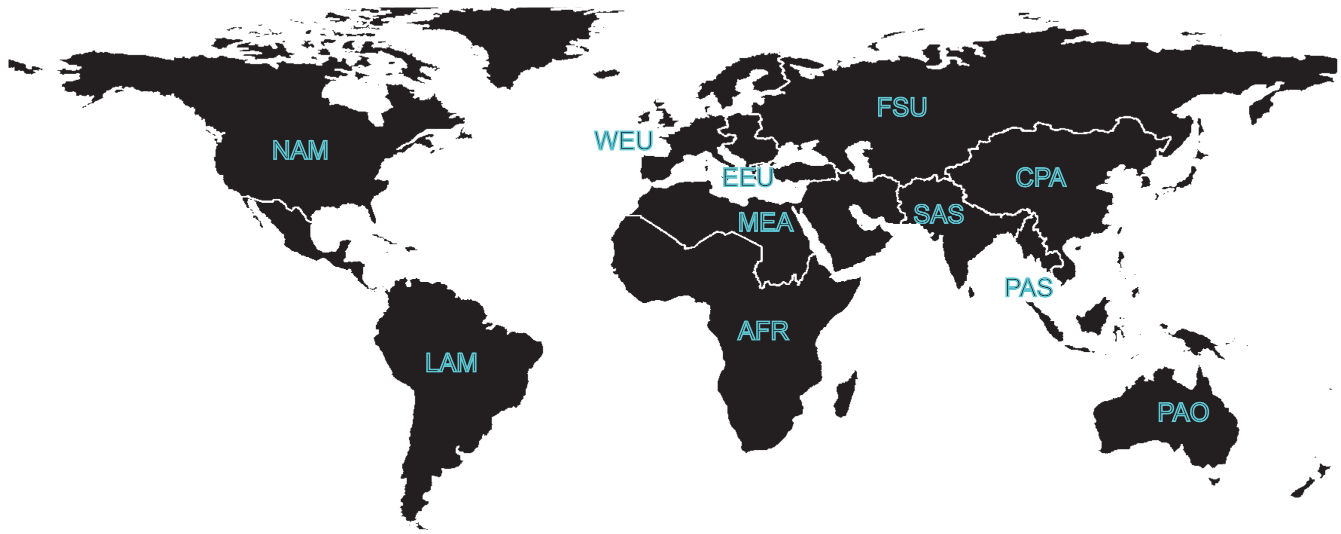

Figure S1: Regional representation of the MESSAGE integrated assessment model (IAM).

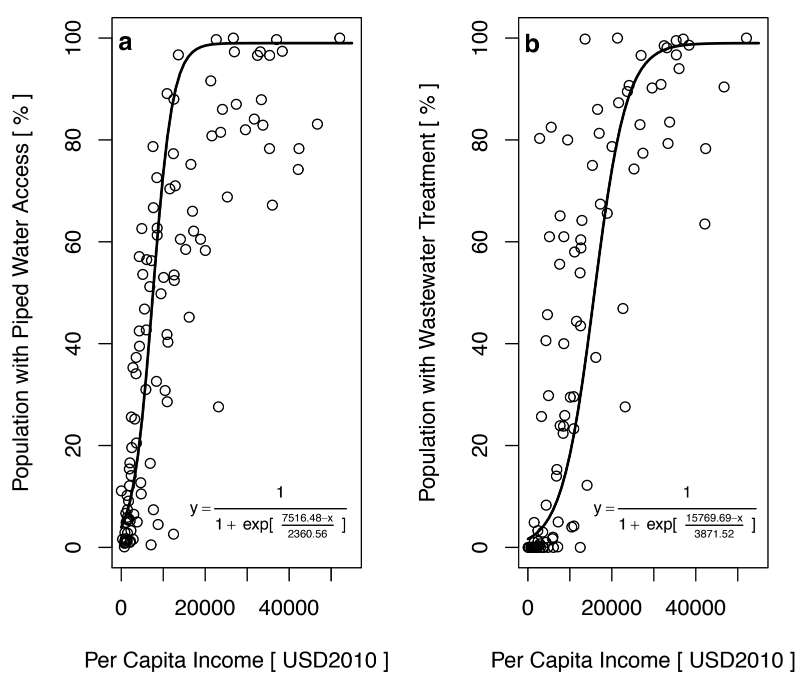

Figure S2: Models for water access and treatment. Logistic models fit between estimated national incomes for 2010 from Dellink et al. (2017) [1], and connection rates from Baum et al. (2013) [2]. In the baseline scenario, countries converge along an exponential path from the estimated historical level towards the modeled connection rate obtained with the future SSP-based income projections. The SDG6 scenarios feature explicit narratives used to set the connection rates directly (i.e., 100% piped water access and 50% wastewater treated by 2030). It is assumed that once a given segment of the population has access to piped water, that they also have access to wastewater collection.

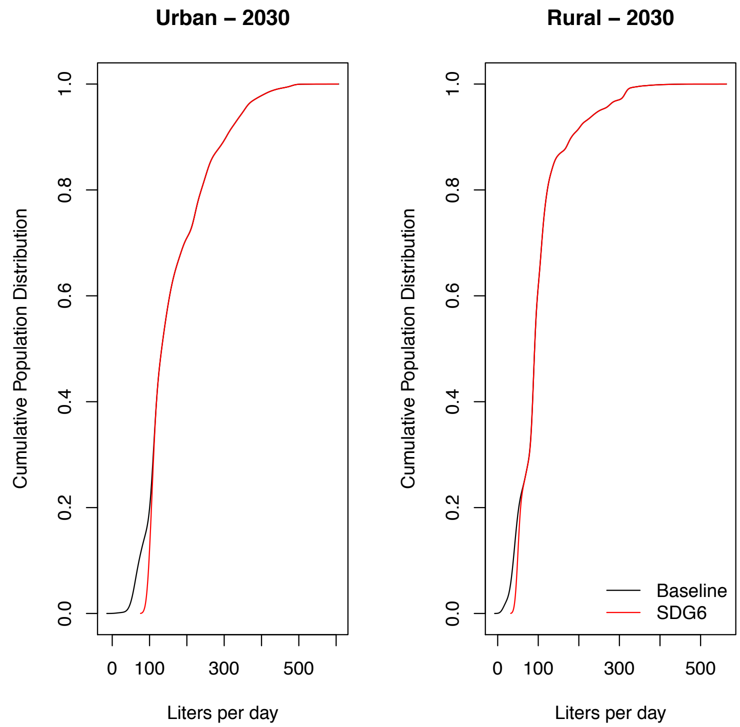

Figure S3: Global distribution of per capita delivered water volumes in 2030 estimated for the urban and rural domestic sectors at 7.5 arc-minutes using the approach described in Parkinson et al. (2016) [3]. Domestic water demands are adjusted in the SDG6 pathways to ensure there is enough water allocated for decent living standards in all locations, which in this paper is translated to a minimum of 100 liters per day in urban areas and 50 liters per day in rural areas [4-6]. Lacking explicit data, the withdrawals and return-flows are adjusted assuming an average efficiency of 75% from source to end-user.

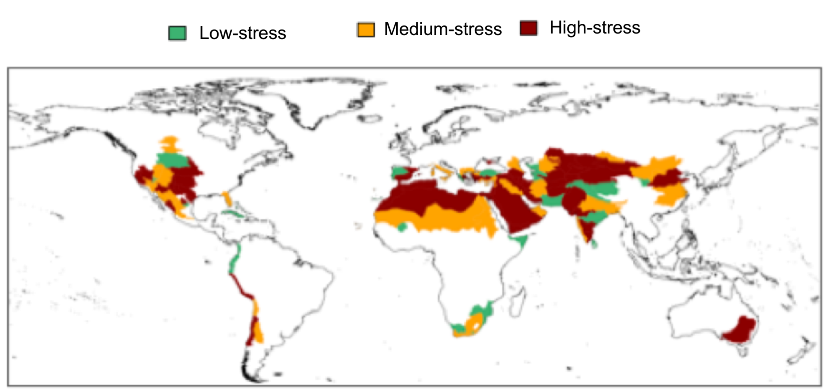

Figure S4: Delineation of water-stressed basin units (ecoregions) following Hoekstra et al. (2010) [7]. Water stress is calculated as the ratio of withdrawals to renewable water availability, and is estimated previously for each ecoregion using data from the WaterGAP global hydrological model [8].

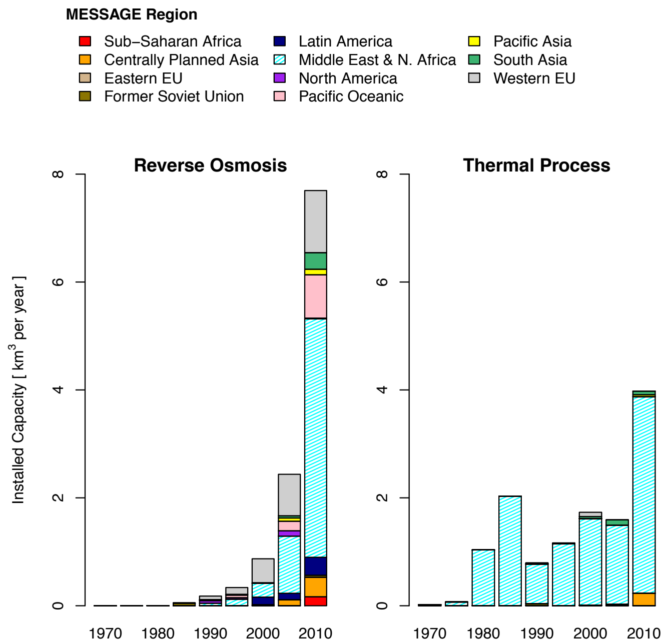

Figure S5: Historical build out of desalination capacity estimated in each MESSAGE region [9].

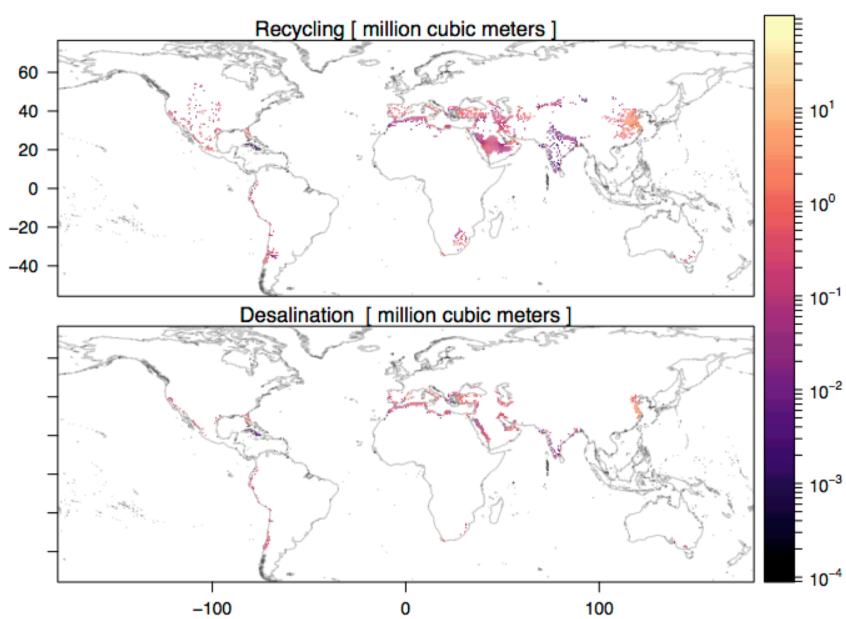

Figure S6: Lower bounds on recycling and desalination production in 2030 at 7.5 arc-minutes in the SSP2 scenario.

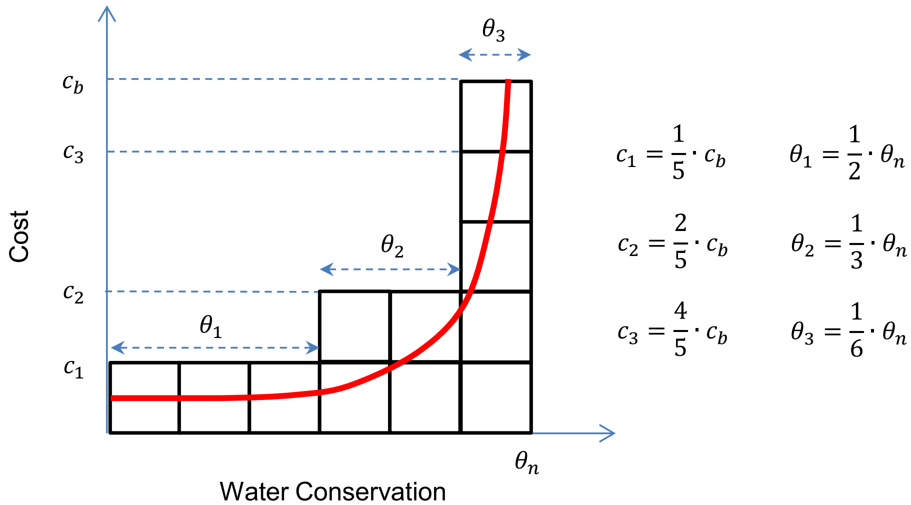

Figure S7: Water conservation curve and linear parameterization used to represent demand response and anticipated implementation costs for end-use conservation measures in MESSAGE. The curve is implemented in the linear program using the indicated step functions. Previous work quantified the impact of diverse conservation options and implementation costs, and generally show that conservation costs increase non-linearly and offset a limited fraction of water demand [10–13]. A maximum conservation potential in each sector representing 30 % of the baseline withdrawals is assumed in this study, and is a somewhat conservative interpretation of previous assessments that focus specifically on water conservation potentials for specific sectors [11-14]. Extending previous work estimating regional-scale water supply expansion costs, we use 0.3 USD per m^3 to represent the average cost for conservation measures because this approximates the point at which it can be expected that investment switches to expanding yield from conventional raw surface and groundwater sources [15].

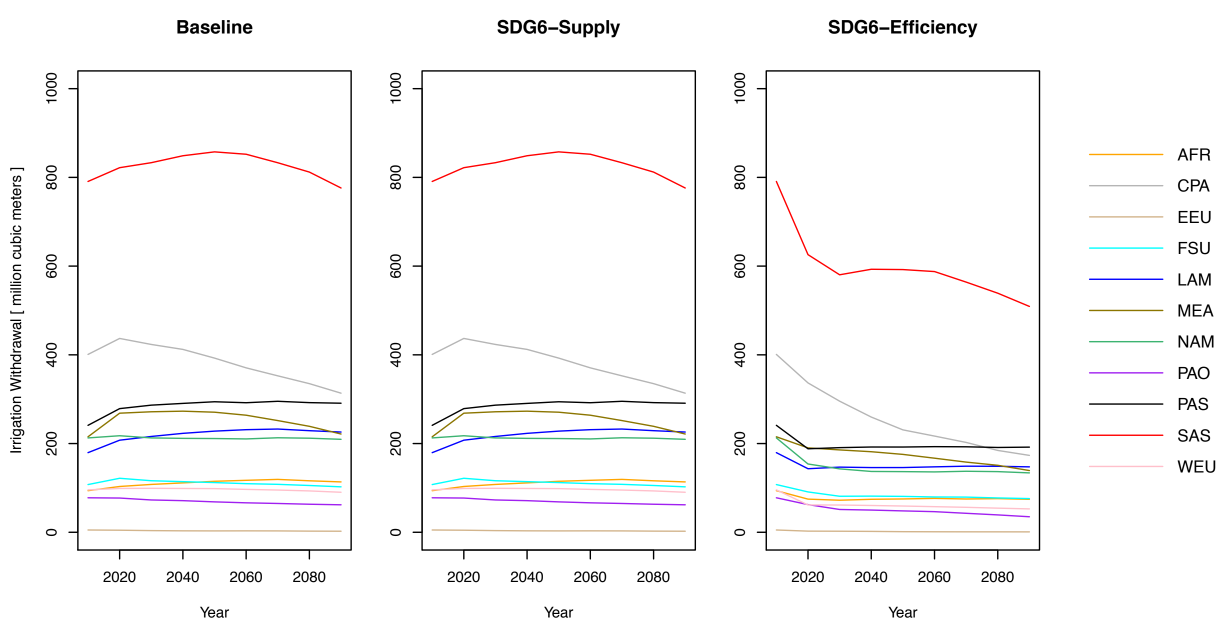

Figure S8: Regional irrigation withdrawal trajectories (after conservation).

Figure S9: Regional urban (municipal + manufacturing) withdrawal trajectories (after conservation).

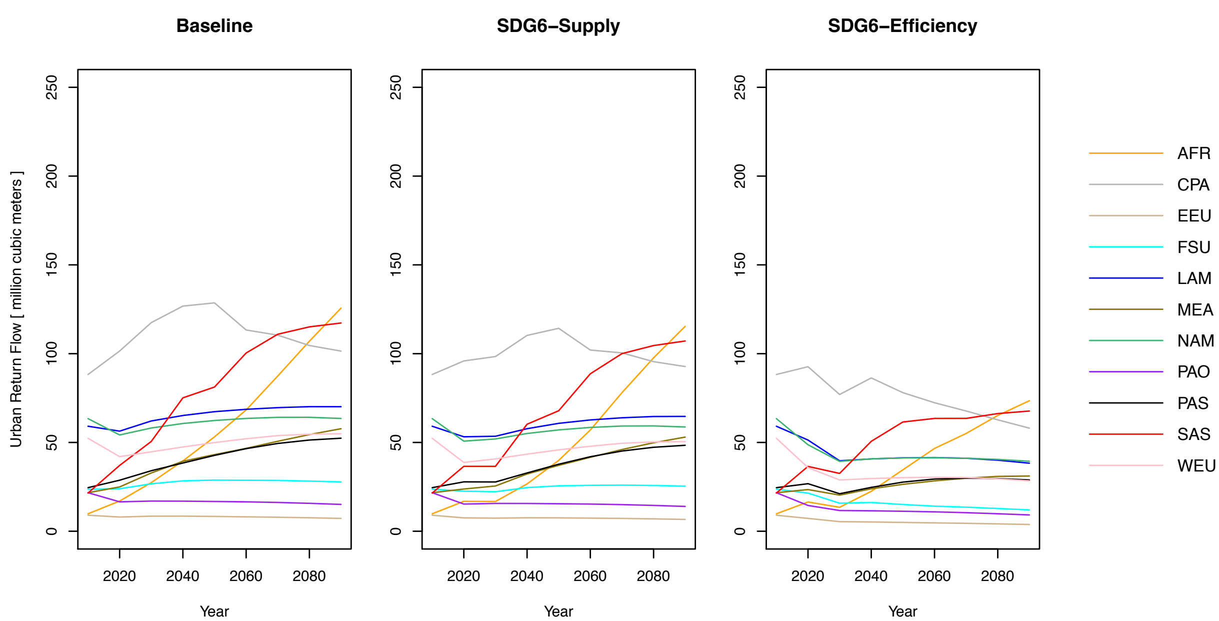

Figure S10: Regional urban (municipal + manufacturing) return-flow trajectories (after conservation).

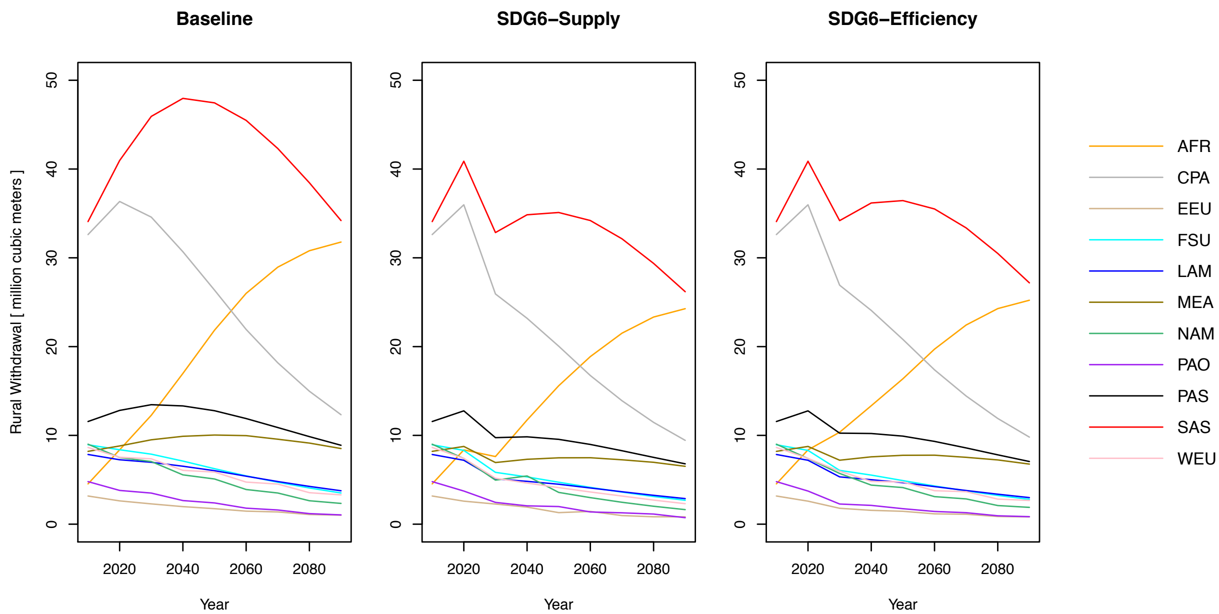

Figure S11: Regional rural (municipal) withdrawal trajectories (after conservation).

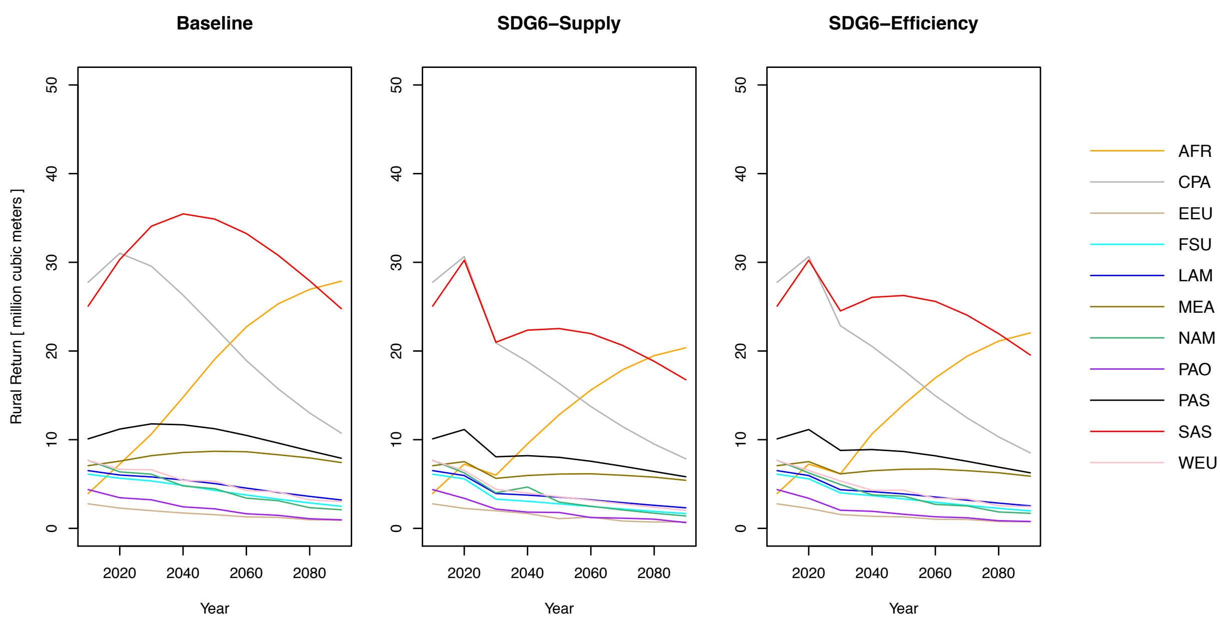

Figure S12: Regional rural return-flow trajectories (after conservation).

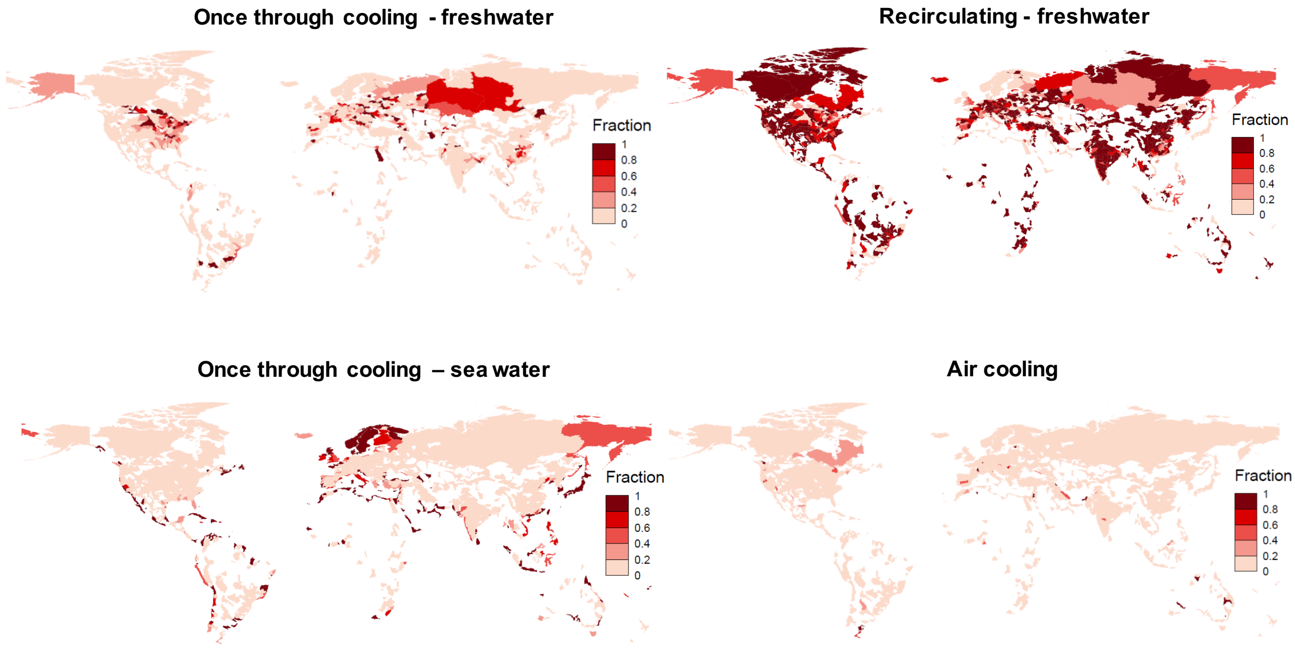

Figure S13: Cooling system shares (fraction of total installed capacity) across all power plants for different cooling system types identified for spatial units representing the intersection of river basins and countries with the facility-level dataset presented in Raptis and Pfister (2016) [16]. Shares are computed for each type of power plant in MESSAGE, and used to define the historical cooling technology capacity. Where data does not exist, the average across all plant types depicted here is used.

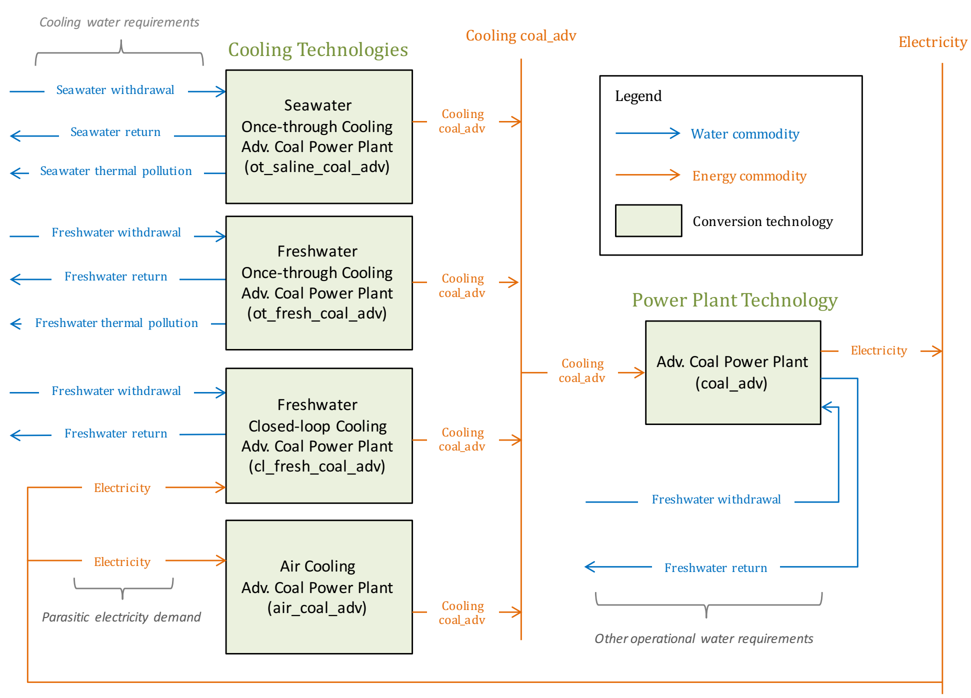

Figure S14: Representation of the power plant cooling technologies in the MESSAGE framework. Power plant cooling is treated as a commodity in the model that must be supplied by specific cooling technologies with unique cost and efficiency impacts.

Table S2 Data for advanced cooling technology costs and electric efficiency. A range of data is identified from the indicated literature sources. Data labelled ‘Efficient’ is used to parameterize technologies in the SDG6-Efficiency scenario. All other scenarios use mid-range data labelled ‘Baseline’.

Cooling Technology	Cycle Type	Parameter	Units	Efficient	Baseline	Source(s)
Recirculating	Single-cycle	Investment cost[2]	USD / kW	110	160	[17,18]
		Electric efficiency[3]	-	0.010	0.017	[18-20]
	Combined-cycle	Investment cost	USD / kW	50	100	[17,18]
		Electric efficiency	-	0.003	0.004	[18-20]
Air cooling[1]	Single-cycle	Investment cost	USD / kW	160	220	[17,18]
		Electric efficiency	-	0.034	0.102	[18-20]
	Combined-cycle	Investment cost	USD / kW	100	140	[17,18]
		Electric efficiency	-	0.025	0.029	[18-20]

1. Air cooling not included for nuclear power plants and carbon capture and storage technologies due to perceived implementation challenges.
2. Other operational costs for cooling systems are accounted for through its energy and water use and the fixed costs for power plants.
3. Efficiency penalty is applied to represent parasitic electricity consumption from additional cooling equipment.

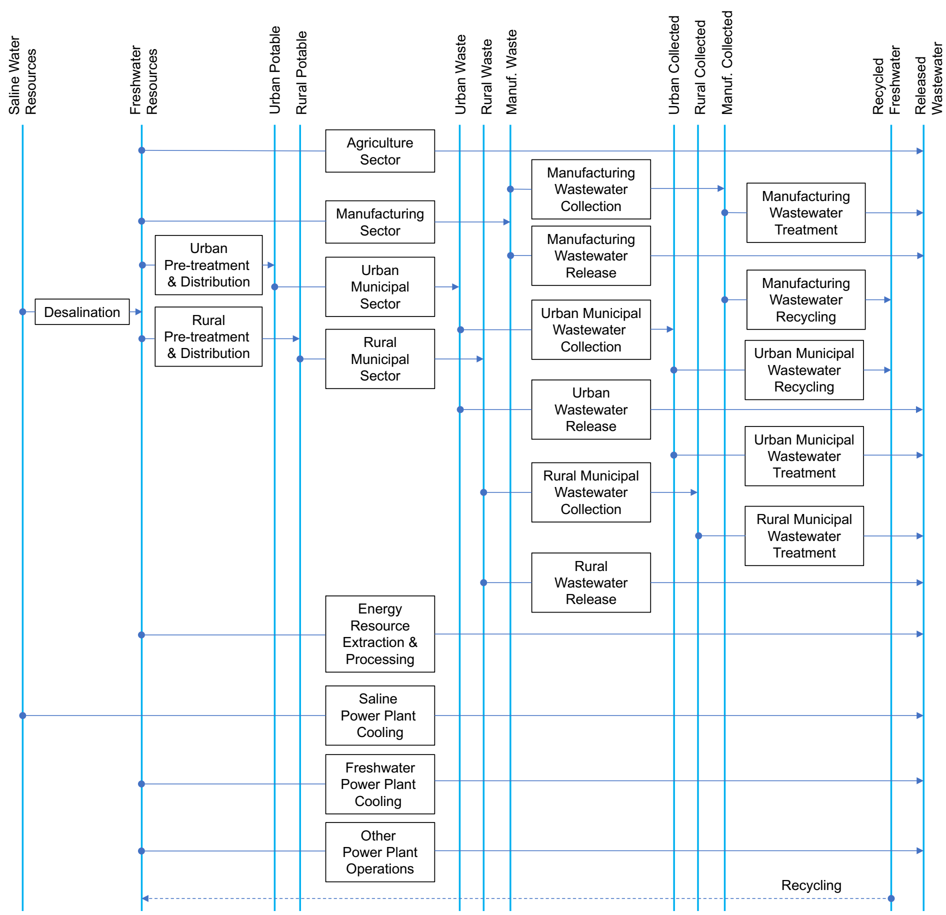

Figure S15: Reduced-form water supply sector representation incorporated into the MESSAGE IAM. The depicted technologies or processes transform water into different qualities. Sectoral water withdrawals and (waste) return-flows are input to the model, excluding energy-related water use, which is accounted for and optimized in MESSAGE at the technology-level. Additional energy inputs and waste outputs for the technologies are included and link the water supply sector to the energy system modeled in MESSAGE.

Table S3: Parameterization of the water supply and wastewater treatment technologies. A range of data is identified from the indicated literature sources. Data labelled 'Efficient' is used to parameterize technologies in the SDG6-Efficiency scenario. All other scenarios use mid-range data labelled 'Baseline'.

Technology / Process	Parameter	Units	Efficient	Baseline	Source(s)
Thermal Desalination[1]	Electricity Intensity	kWh / m^3	1.5	3.0	[21,22]
	Thermal Intensity	kWh / m^3	4.0	9.0	[23]
	Water efficiency	-	0.40	0.35	[23]
	Capital Cost	USD / m^3	4.79	5.21	[21]
	Fixed Cost	USD / m^3	0.48	0.52	Assumed 10% capital cost
	Lifetime	years	40	30	[21,23]
Membrane Desalination	Electricity Intensity	kWh / m^3	3.0	4.0	[21,22]
	Water efficiency	-	0.45	0.40	[23]
	Capital Cost	USD / m^3	3.56	4.52	[21]
	Fixed Cost	USD / m^3	0.36	0.45	Assumed 10% capital cost
	Lifetime	years	40	30	[21,23]
Urban Wastewater Treatment	Electricity Intensity	kWh / m^3	0.13	0.38	[23]
	Water efficiency	-	0.95	0.90	[24]
	Capital Cost	USD / m^3	0.83	1.18	[24]
	Fixed Cost	USD / m^3	0.06	0.10	[24]
	Lifetime		40	30	[24]
Rural Wastewater Collection and Treatment[2]	Electricity Intensity	kWh / m^3	0	0	Assumed
	Water efficiency	-	0.97	0.95	Assumed
	Capital Cost	USD / m^3	0.66	2.08	[25-27]
	Fixed Cost	USD / m^3	0.07	0.21	[25-27]
	Lifetime	years	25	20	[25]
Urban / Manufacturing Wastewater Recycling[3]	Electricity Intensity	kWh / m^3	0.80	1.00	[23]
	Water efficiency	-	0.85	0.80	[24]
	Capital Cost	USD / m^3	2.76	3.70	[24]
	Fixed Cost	USD / m^3	0.17	0.27	[24]
	Lifetime	years	40	30	[24]
Urban / Manufacturing Water Distribution	Electricity Intensity[4]	kWh / m^3	0.10	0.20	[23]
	Capital Cost	USD / m^3	1.49	2.77	[25-27]
	Fixed Cost	USD / m^3	0.62	0.69	[25-27]
	Lifetime	years	50	40	[25-27]
Urban / Manufacturing Wastewater Collection	Electricity Intensity[5]	kWh / m^3	0	0	Assumed
	Capital Cost	USD / m^3	1.16	2.15	[25-27]
	Fixed Cost	USD / m^3	0.29	0.54	[25-27]
	Lifetime	years	50	40	[25-27]
Rural Water Distribution	Electricity Intensity[4]	kWh / m^3	0.10	0.20	[23]
	Capital Cost	USD / m^3	0.67	0.90	[25-27]
	Fixed Cost	USD / m^3	0.03	0.05	[25-27]
	Lifetime	years	50	40	[25-27]

1. For simplification, thermal desalination technologies are parameterized to represent multi-stage flash and distillation options.
2. Representative of a common septic system. Additional energy requirements are expected to be negligible.
3. For simplification, the same technology is used to represent manufacturing and urban municipal wastewater recycling.
4. Electricity intensities for pumping reflect averages for surface and groundwater systems and do not account for long-distance transfers.
5. Electricity intensities for wastewater pumping are allocated to the treatment and recycling technologies and reflect averages.

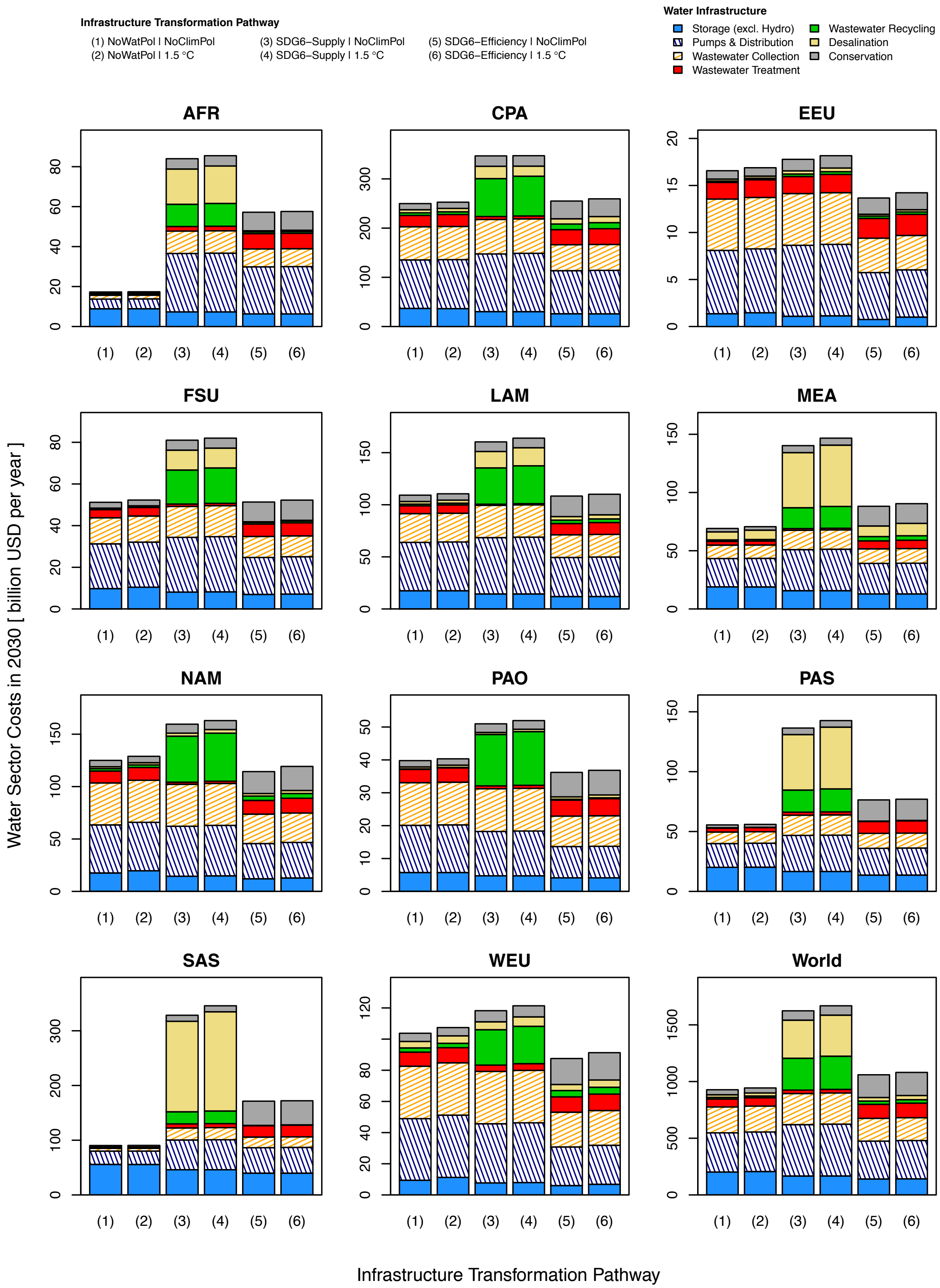

Figure S16: Water sector costs in 2030 in each MESSAGE region and globally.

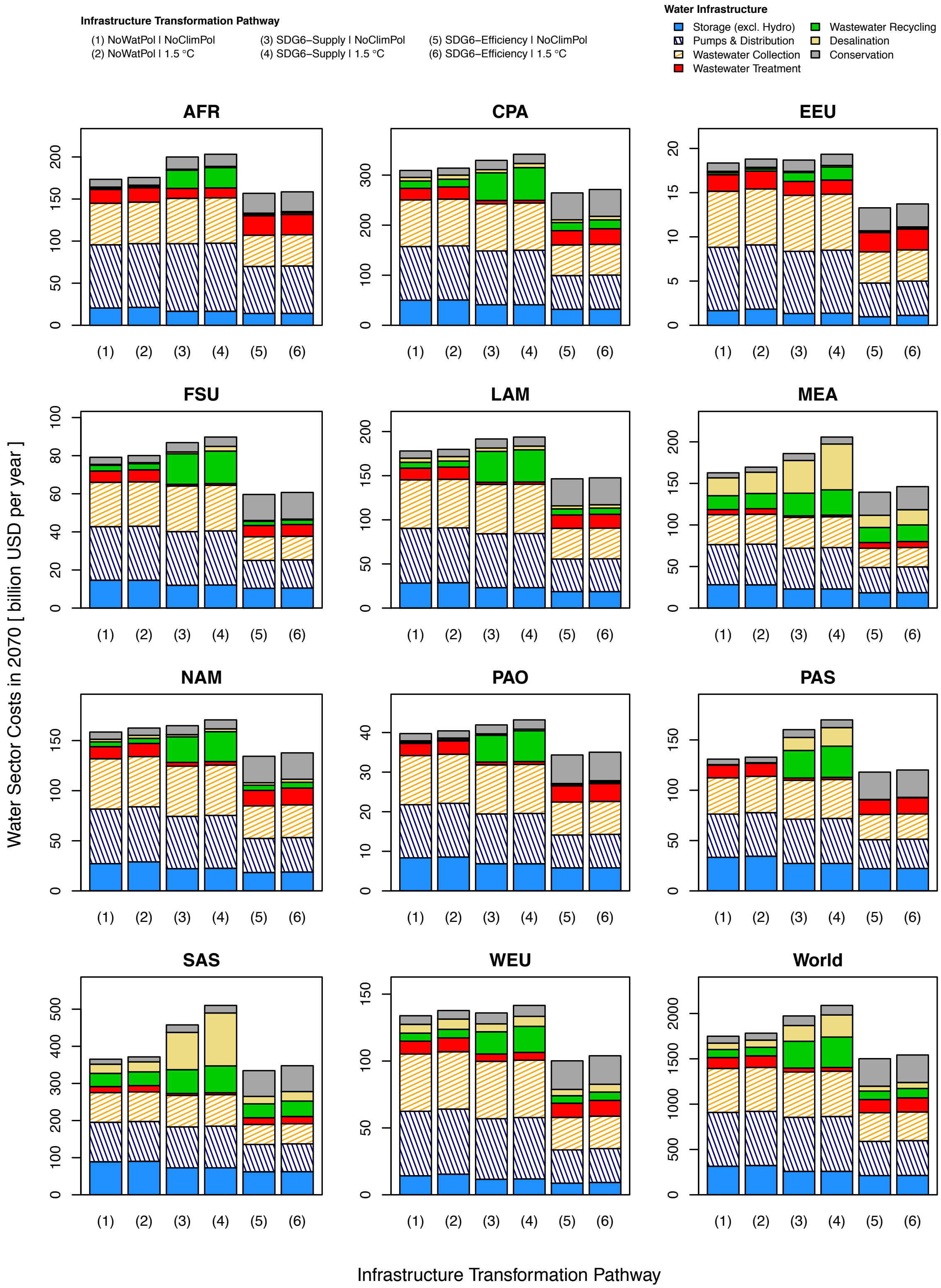

Figure S17: Water sector costs in 2070 in each MESSAGE region and globally.

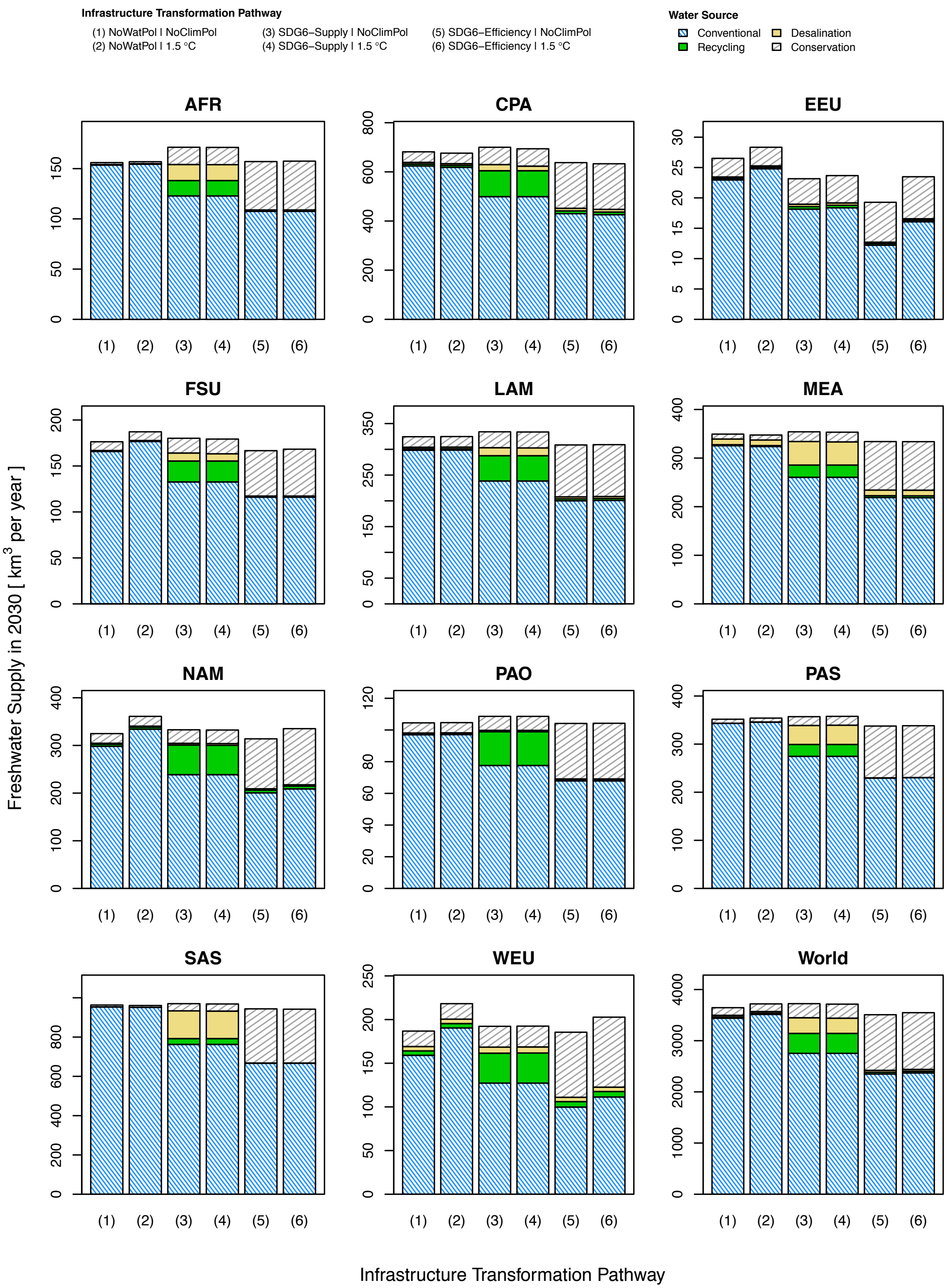

Figure S18: Water supply mixture in 2030 for each MESSAGE region and globally.

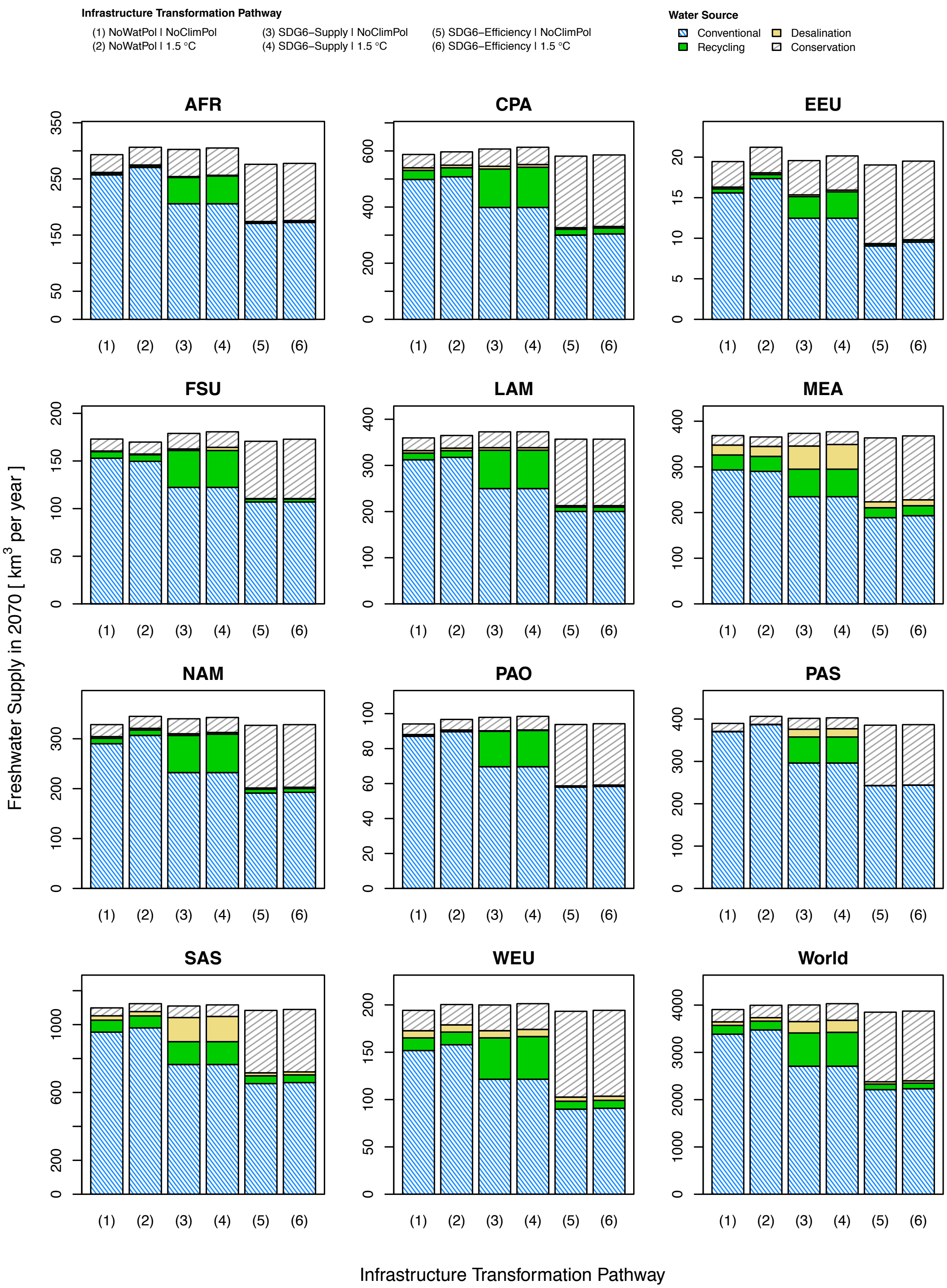

Figure S19: Water supply mixture in 2070 for each MESSAGE region and globally.

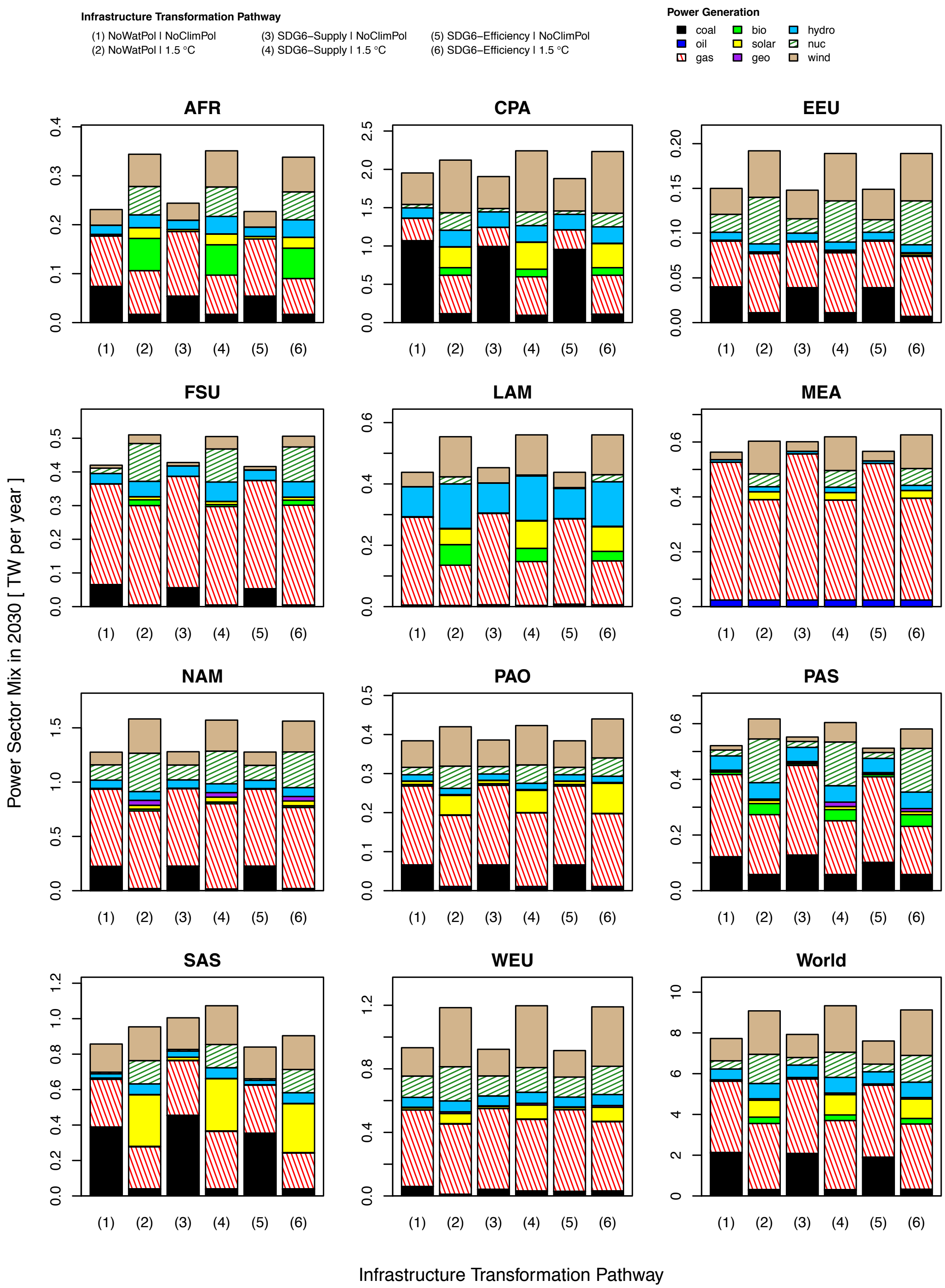

Figure S20: Power generation mixture in 2030 for each MESSAGE region and globally.

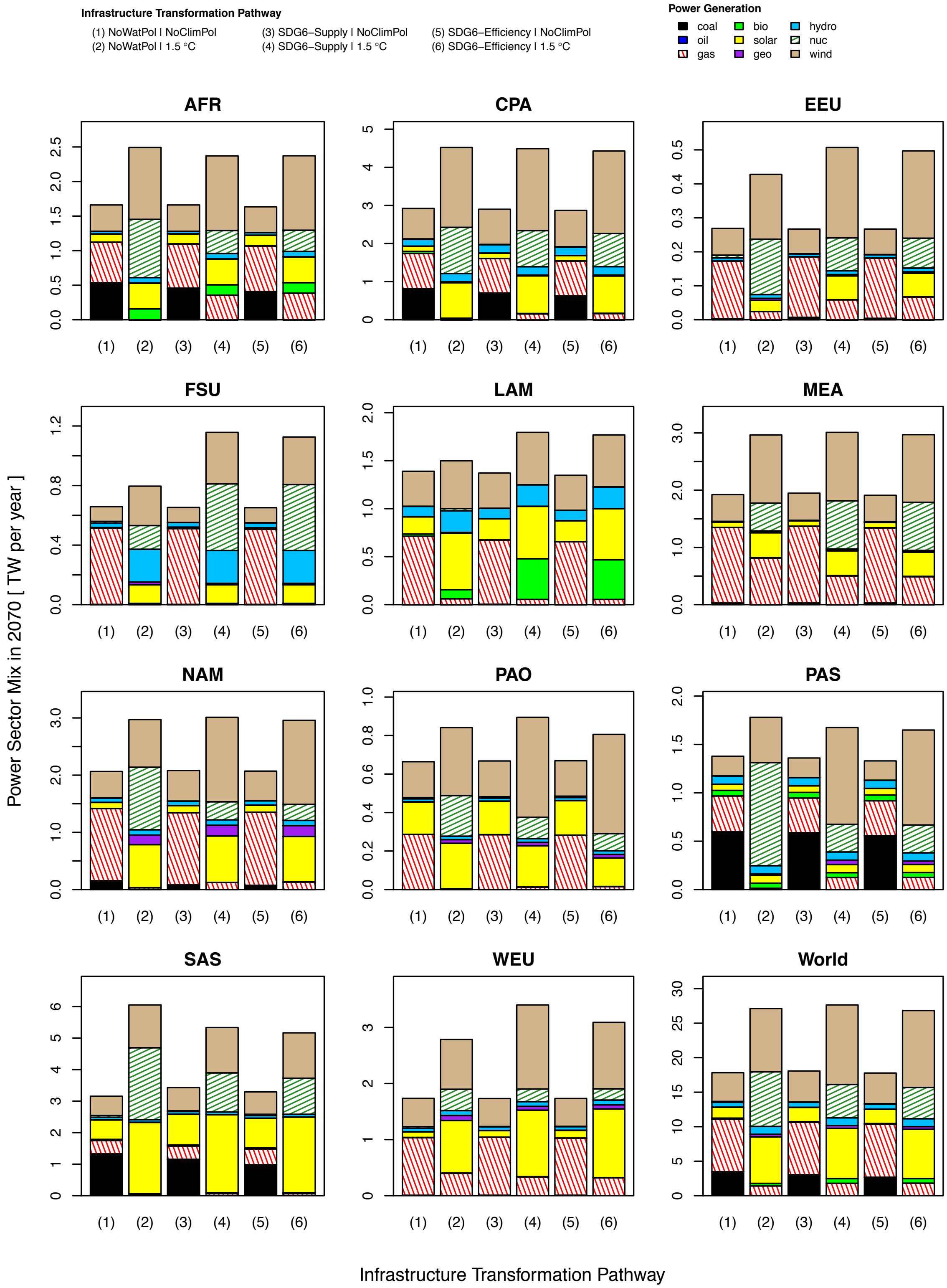

Figure S21: Power generation mixture in 2070 for each MESSAGE region and globally.

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