Water use in the US energy system:

A national assessment and unit process inventory of water consumption and withdrawals

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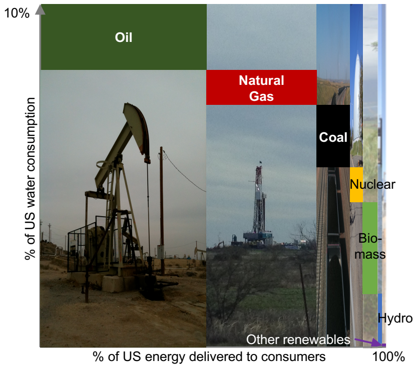
Abstract: The US energy system is a large water user, but the nature of that use is poorly understood. To support resource co-management and fill this noted gap in the literature, this work presents detailed estimates for US-based water consumption and withdrawals for the US energy system as of 2014, including both intensity values and the first known estimate of total water consumption and withdrawal by the US energy system. We address 126 unit processes, many of which are new additions to the literature, differentiated among 17 fuel cycles, five life cycle stages, three water source categories, and four levels of water quality. Overall coverage is about 99% of commercially traded US primary energy consumption, with detailed energy flows by unit process. Energy-related water consumption, or water removed from its source and not directly returned, accounts for about 10% of both total and freshwater US water consumption. Major consumers include biofuels (via irrigation), oil (via deep well injection, usually of non-freshwater), and hydropower (via evaporation and seepage). The US energy system also accounts for about 40% of both total and freshwater US water withdrawals, i.e., water removed from its source regardless of fate. About 70% of withdrawals are associated with the once-through cooling systems of approximately 300 steam cycle power plants that produce about 25% of US electricity.

Table of Contents / Abstract Art:



Introduction.

The US energy system requires water for primary energy extraction, processing and refining, conversion to secondary forms, waste disposal, and site remediation[1]. Interlinkages between water and energy systems, often called the "energy-water nexus," are well documented[2–6], but the energy system's demand for water has not been comprehensively quantified with data reflecting major changes to the energy system from the last several decades. Total energy consumption in the United States is flattening, while the domestic energy supply is expected to continue to grow[7]. On the supply side, both the US fuel mix and the technologies used to supply energy to consumers are changing, most significantly via more deployment of renewable electricity technologies[8–10]; more unconventional oil and natural gas extraction[11–23]; tighter environmental controls in the power sector, particularly affecting coal ; and diversification of fuel sources in the transportation sector[26–29]. Consequently, one of the major policy concerns of the energy-water nexus is the effect of this dynamic energy system on volumetric water resource demands.

Energy system transitions are associated with diverse incentives (e.g., economics, policy, social pressures, etc.) and industries (e.g., oil and gas, power generation, transportation) on different spatio-temporal scales, making a holistic approach to energy and water co-management difficult. Efforts to inventory overall water use are hampered by inconsistency, incompleteness, and age of individual water intensity estimates, which, in many instances, can be traced back to sources that are many decades old and based on outdated processes. As a result, the overall water use of the energy system is poorly understood, despite the existence of detailed inventories for other aspects of the energy sector, including electricity generation and fuel use, air emissions, and production[30–33].

Co-management of energy and water resources is becoming increasingly important as challenges such as extended drought, climate change, and population growth add pressure to freshwater resources, especially in water-constrained regions[34–43]. Recent historic droughts in California, Texas and other parts of the southwestern US have drawn attention to water provisioning for energy-related uses, as well as farming and direct human consumption[17,44,45]. Water constraints have not been limited to drought-prone regions: even relatively water-rich regions have faced water-related energy curtailments over the past decade.

Water concerns are attracting more attention to water resource use prior to and following energy development. Regulators and the public are explicitly raising concerns about water use at energy facilities[46,47], prompting interest in dry cooling and alternative cooling sources[42,48–51]. Non-traditional water sources are being explored as alternatives to freshwater for oil and gas, biofuels, and the power sector[49,52–56]. Given growing concerns about seismicity[57–61], management costs[12,16,62–64], and regional drought[22,65], there is increasing interest in reuse opportunities[22,64,65] and beneficial uses of produced water[66–68] in regions that withdraw large volumes of water during oil and gas development, like California, Oklahoma, and Texas.

Despite the escalating importance of sustainable water management, serious data gaps exist, impeding the holistic management of water resources[37,41,69,70,71]. One of the most consequential gaps is that national water consumption has not been federally estimated since 1995[72]. Some of this mismatch is due, in part, to lower requirements for federal water reporting and forecasting versus energy reporting and forecasting[73]. Although the United States Geological Survey (USGS) estimates water withdrawals for the entire US economy[74], estimates are only made every five years, with a multi-year lag and low resolution on processes and sectors. For example, "mining" is a single category and does not distinguish between energy and non-energy resources, oil and natural gas versus solid resources, etc. More specific data do exist for some aspects of the energy and other sectors, but they are often fragmented due to state-level reporting, variable definitions related to characterizing water quantity and quality, proprietary classifications, and different vintages[41,68,75]. Policy makers, businesses, and individuals are increasingly called upon to consider water impacts before making decisions[76], but no agency is currently empowered to collect and provide internally consistent data at the temporal and process scales that are needed. Similarly, water quantity is often excluded from sustainability-oriented decision support tools like life cycle assessment because of data and definitional challenges[77], even though water quantity is a consistently high priority issue for the American public[78].

To the authors' knowledge, there has not been a comprehensive effort to characterize water consumption and withdrawal for the US energy system since 1980[79], when the Department of Energy (DOE) compiled process-level water intensity data for nuclear, coal, petroleum, natural gas, synthetic fuels, solar energy, geothermal energy, and hydroelectricity. This DOE study is a major source for the better known Gleick compilation of intensity estimates[80], which is in turn a major source for many of the more recent energy-water nexus studies addressing water intensity of energy systems[81–83]. No overall estimate of the water volumes withdrawn and consumed by the energy system currently exists.

Given the many changes to the energy system over the past several decades, including the rise of unconventional hydrocarbon development and renewable energy, and given calls for more integration between energy and water policy[40,41,68,70,75], both total volume and updated intensity estimates that reflect current practice in the energy industries are needed. This work provides the first known estimate of total US water use for energy, covering over 99% of the US energy system using a base year of 2014, the most recent year for which data were available across the energy system as of this writing. Further, we present detailed data differentiated by water quality, source, and use type (i.e., consumption or withdrawal) for 126 processes, in many cases based on new analysis and addressing processes not previously present in the literature (see Supplementary Information, SI (184 pages), for detailed descriptions). These data are critical to supporting better decision making about co-management of vital water and energy resources[37], both of which are important to societal function and are likely to experience significant dynamism because of climate and technology change[84].

The goal of this work is twofold and makes several contributions to the energy, water, and environmental sustainability literatures. First, we provide a high resolution dataset for use in activities like life cycle assessment, integrated water resources management, and other analytical processes that can benefit from understanding the implications of energy resource use for water withdrawals and consumption in the United States. This primary contribution is the publication of a near-comprehensive set of current values for water withdrawal and consumption for the US energy system, using consistent assumptions across resources. Unlike other work in this area, this research develops both absolute numbers and intensity factors for water withdrawals and consumption. As a result, we provide estimates for the total water withdrawn and consumed for the US energy system, which do not currently exist in the literature. In addition, this research presents data differentiated by life cycle stage, water source, and water quality for both withdrawals and consumption, which similarly are not currently present in the literature for the whole energy system. Second, we highlight that the current state of data availability and data precision regarding water used for energy systems is inadequate to support ongoing energy-water nexus decision making. Resource co-management requires more effort both in data collection and in the research community's commitment to using consistent and precise definitions.

Methods.

This work covers systems accounting for an estimated 99.4% of US primary commercial energy consumption for 2014 (see Data File S1), where commercial refers to energy that is bought and sold as a commodity not for use as food, feed, or feedstock, excluding resources like passive solar, informal biomass, and off-grid applications. We examine the water withdrawn and consumed for the US energy system across 17 fuel cycles (liquid fuels: conventional oil, unconventional oil, ethanol, and biodiesel; electricity and industrial fuels: subbituminous coal, bituminous coal, lignite coal, conventional natural gas, unconventional natural gas, uranium, hydropower, wind, solid biomass and refuse-derived fuels (RDF), biogas, geothermal, solar photovoltaic, and solar thermal), using mass transfer-based definitions for water withdrawal and consumption (see SI, page S9, for complete definitions). Water withdrawals and consumption for each fuel cycle are investigated across individual processes assigned to one of five life cycle stages: production (extraction/capture), processing, transport, conversion (power generation and refining), and post-conversion, with detail for 126 unit processes presented in Data File S1. Water formed during hydrocarbon combustion[85] is also reported separately in Data File S1 for reference but, because the ultimate fate of this combustion water is unknown, estimates for withdrawal and consumption do not include combustion water. Water withdrawals and consumption are further categorized by water source (surface water, groundwater, or reuse) and water quality (freshwater, brackish water, saline water, or "not reverse osmosis (RO) treatable"—water too saline for treatment by reverse osmosis). We include "not RO treatable" water as its own category because of the practical cost and technological limitations on management options for these very saline waters.

The underlying analysis for this work draws on over 300 primary and secondary sources, in addition to contributing new results computed based on physical relationships. Empirical data collected for the year of study are prioritized when available, followed by compilations of recent data, direct communication with operators, pre-operational estimates, and finally, calculated values based on physical relationships. Where necessary, data are converted to the 2014 base year using scaled proxies chosen based on their correlation with water demand (e.g., re-scaling estimates for water used for oil well drilling is based on well borehole volume rather than on the amount of oil produced, as water use volumes are mediated by the volume of the well, not oil production from the well). Our dataset also provides water use intensity estimates using multiple bases (i.e., volumetric water usage per unit of energy to which a given process applies versus per unit of energy delivered to a consumer) and an accounting of the amount of energy associated with each water-using process, validated against EIA records for 2014[86].

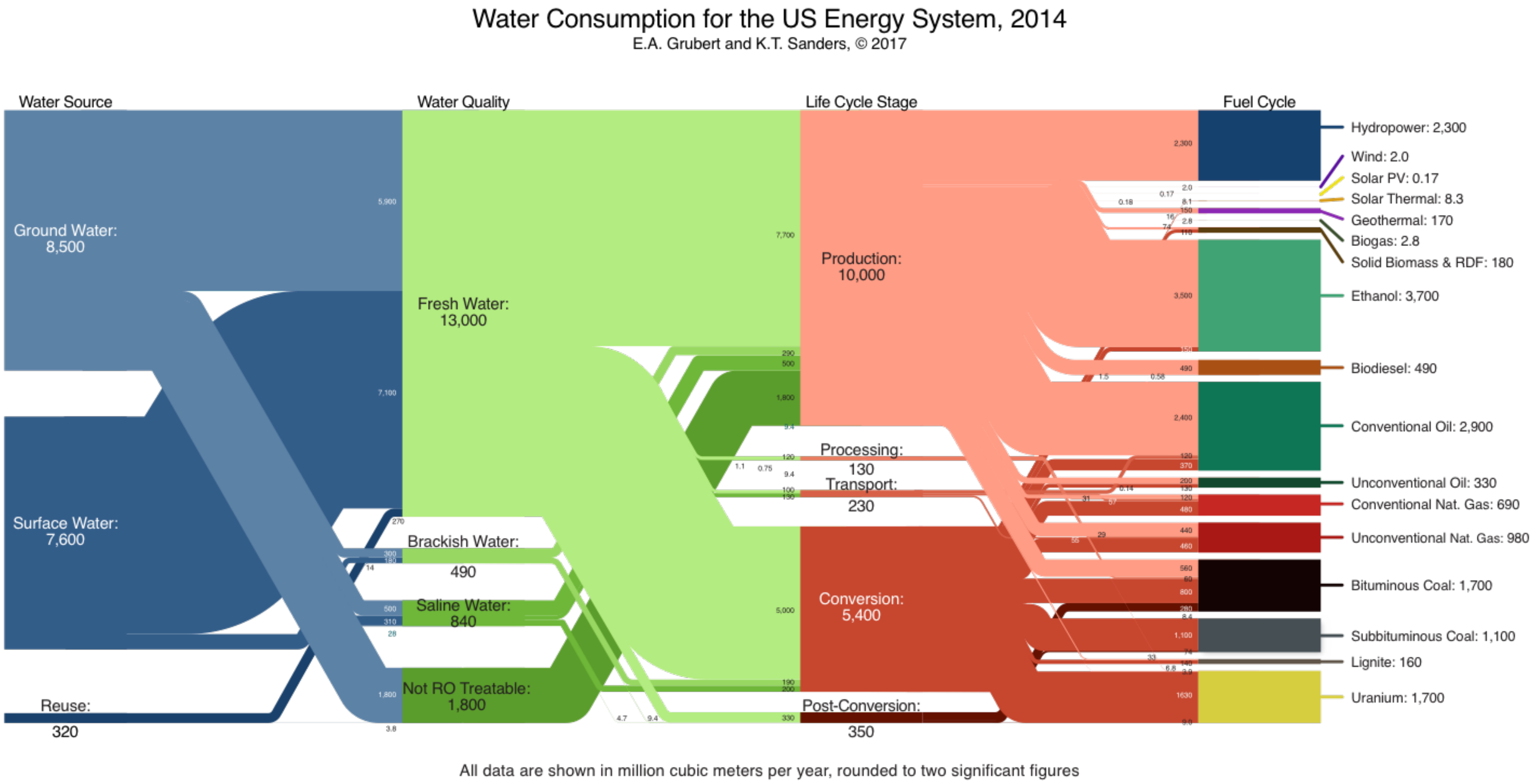
Water withdrawn and consumed within the US for direct, operational needs (i.e., unit process use) of the commercial energy system is included in the analysis, whether it is used for imported energy, exported energy, or fully domestic energy. Discharge volumes are not carefully tracked, though return flows (the portion of water withdrawals returned to the same source) have been calculated based on consumption estimates. Note that discharges and return flows are not identical, as discharge can be a consumptive use: for example, groundwater can be discharged to a surface water body. Any water consumed or withdrawn outside the US is excluded, even for non-US-origin fuel ultimately consumed in the US (e.g., in the case of imports) or US-origin fuels consumed outside the US (e.g., in the case of exports). Embodied water is also excluded from analysis, including water embodied in consumables like proppant (for hydraulic fracturing) or fertilizer (for biofuels). Note that this work does not address quality impacts (thermal, chemical, or otherwise) related to use.

Full numerical results, definitions, assumptions, limitations, and details on calculations are provided in the SI, which is organized by fuel. We draw attention to several major assumptions here. This work uses mass transfer-based definitions for withdrawal and consumption, such that any removal of water from its proximate source is considered a withdrawal and any withdrawal not returned to that source is consumptive (see also SI, page S9). Though this definition and minor variants are commonly used in the literature[87], they are inconsistently applied. For example, groundwater discharged to surface water or nondiscretionary produced water from oil wells disposed in deep wells is consumed by definition but is frequently characterized otherwise. This work also makes several resource-specific assumptions of potential broad interest. Produced water from fossil resource extraction is treated like any other groundwater abstraction, with the important implication that produced water used for enhanced oil recovery is withdrawn but not consumed, as it is returned to its original aquifer. For biofuels and biomass, only irrigation water is considered a potential withdrawal or consumptive use. That is, biomass fuels are actually more water intensive than this work reflects due to rainfall and soil moisture contributions to evapotranspiration. In cases where coproducts are important (namely for biofuels and hydropower), allocation proceeds based on a principle of additionality: what activity likely prompted the water use? For biofuels, water is allocated based on financial value (see SI). For hydropower, water is allocated based on a given reservoir's stated primary purpose, or the major reason the reservoir was created (see SI and Grubert[88] for an extensive discussion of this choice and its implications, including sensitivity analysis to other allocation approaches). Hydropower's water consumption is presented net of anticipated groundcover evapotranspiration[88] and includes losses from both evaporation and seepage.

Results and Discussion.

Figures 1 and 2 display water consumption and withdrawals for the US energy system in 2014. We find that the energy sector is responsible for approximately 10% (1.6×10^{10} m^3 per year) of total US water consumption, with the largest overall consumers being irrigation for corn used for ethanol (freshwater), produced water from oil extraction (non-freshwater), and evaporation from hydroelectric reservoirs (freshwater). Note that water abstracted from groundwater aquifers and not returned is a consumptive use, regardless of aquifer depth or whether the aquifer is fresh (as for irrigation) or not (as for oil extraction). Specifically, using a mass transfer-based definition of consumption, groundwater discharge to surface water or to a different aquifer is a consumptive use, just as surface water transfer to groundwater (e.g., for agriculture) or hydrologically disconnected surface water basins is. We also find that the energy sector (excluding nonconsumptive hydropower withdrawals) is responsible for 40% (2.2×10^{11} m^3 per year) of US water withdrawals (see SI for a discussion of nonconsumptive hydropower withdrawals, estimated at about 2×10^{13} m^3 per year—100 times all other energy-related withdrawals combined and thus excluded from Figure 2).

Fig. 1. Water consumption for the US energy system, 2014, million cubic meters (10^6 m^3).


Water Consumption for the US Energy System, 2014

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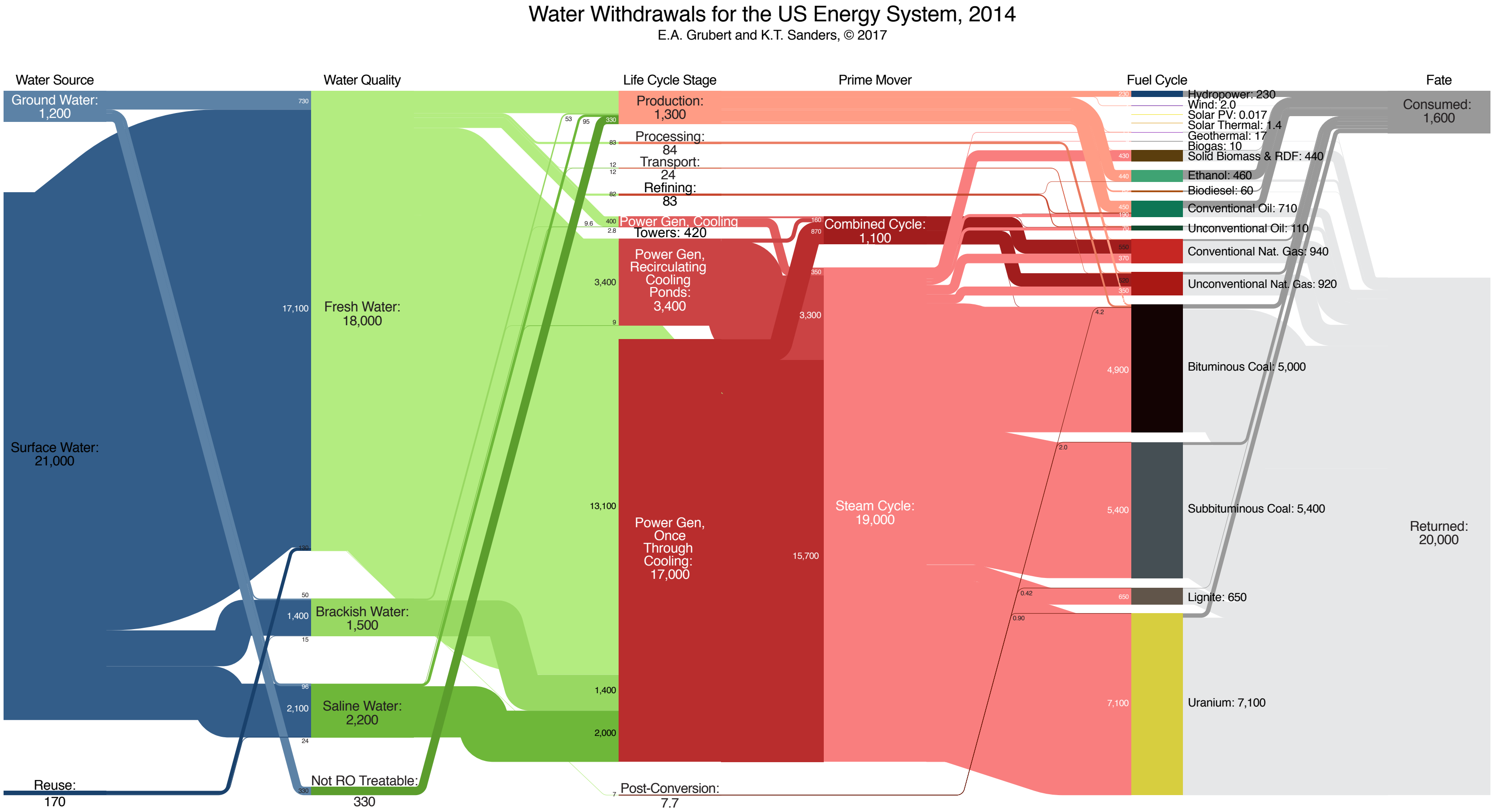
All data are shown in million cubic meters per year, rounded to two significant figures

Fig. 2. Water withdrawals for the US energy system excluding nonconsumptive hydropower withdrawals, 2014, ten-million cubic meters (10^7 m^3).

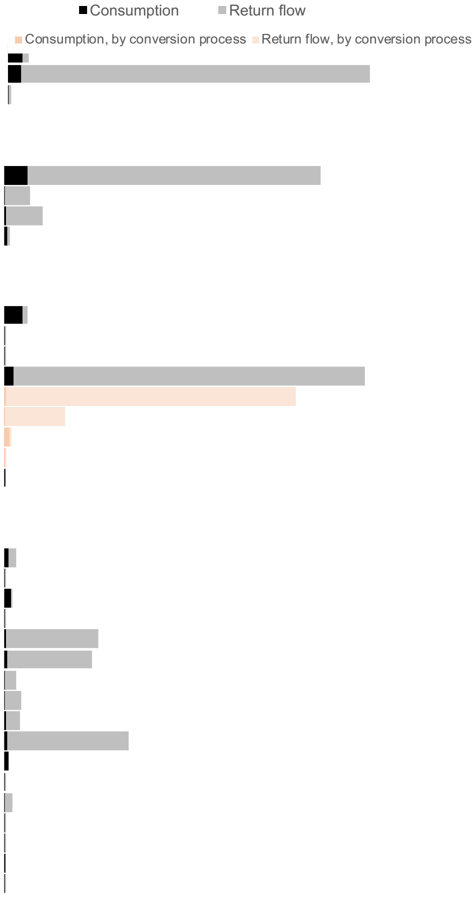


All data are shown in 10 million cubic meters per year, rounded to two significant figures

Overall, both energy-related water consumption and withdrawals are primarily freshwater. Energy-related water consumption is primarily groundwater and related to production-stage activities, while withdrawals are primarily surface water and related to conversion-stage activities, mainly power plants (Fig. 3). Consistent with previous findings[74], we find that thermoelectric power plants represent the main demand for water withdrawals. Our analysis further shows that these withdrawals are dominated (~75% of power plant withdrawals and ~70% of total energy-related withdrawals) by once-through cooling systems at about 300 steam turbine-based thermoelectric power plants that generate about 25% of US electricity. Regulations targeting this relatively small population of power plants are therefore likely to have a large impact on the overall withdrawal intensity of the US energy system.

Fig. 3. Quantitative summary of total water consumption and withdrawals for US energy system, excluding nonconsumptive hydropower withdrawals, 2014 (see also Data File 1 in the Supplementary Information)

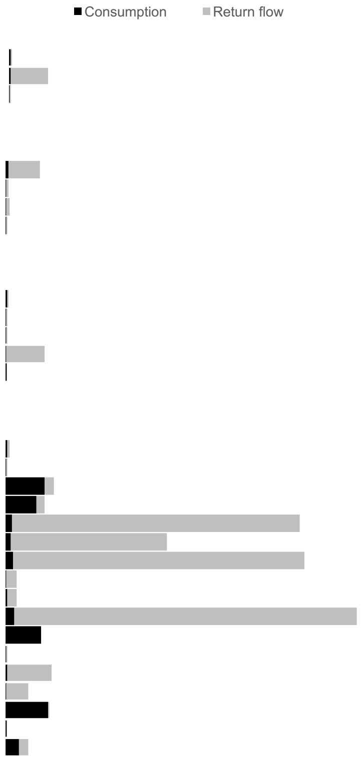
	Consumed, cubic meters (2014)	Withdrawn, cubic meters (2014)	Returned to source, cubic meters (2014)
Water Source			
Ground	8.5E+09	1.2E+10	3.6E+09
Surface	7.5E+09	2.1E+11	2.0E+11
Reuse	3.2E+08	1.7E+09	1.3E+09
Total	**1.6E+10**	**2.2E+11**	**2.0E+11**
Water Quality			
Freshwater	1.3E+10	1.8E+11	1.7E+11
Brackish Water	4.9E+08	1.5E+10	1.4E+10
Saline	8.3E+08	2.2E+10	2.1E+10
Not RO Treatable	1.8E+09	3.3E+09	1.5E+09
Total	**1.6E+10**	**2.2E+11**	**2.0E+11**
Life Cycle Stage			
Production	1.0E+10	1.3E+10	3.2E+09
Processing	1.3E+08	8.4E+08	7.1E+08
Transport	2.3E+08	2.4E+08	8.8E+06
Conversion	5.3E+09	2.0E+11	2.0E+11
Power Gen, Once Through Cooling	*1.0E+09*	*1.7E+11*	*1.6E+11*
Power Gen, Recirculating Cooling Ponds	*5.5E+08*	*3.4E+10*	*3.4E+10*
Power Gen, Recirculating Cooling Towers	*3.1E+09*	*4.2E+09*	*1.0E+09*
Refining	*5.9E+08*	*8.3E+08*	*2.4E+08*
Post-conversion	3.7E+08	7.7E+07	-
Total	**1.6E+10**	**2.2E+11**	**2.0E+11**
Fuel Cycle			
Conventional oil	2.9E+09	7.1E+09	4.2E+09
Unconventional oil	3.2E+08	1.1E+09	7.4E+08
Ethanol	3.7E+09	4.5E+09	8.6E+08
Biodiesel	4.9E+08	6.2E+08	1.3E+08
Subbituminous coal	1.1E+09	5.4E+10	5.2E+10
Bituminous coal	1.7E+09	5.0E+10	4.8E+10
Lignite	1.6E+08	6.5E+09	6.3E+09
Conventional natural gas	7.0E+08	9.4E+09	8.7E+09
Unconventional natural gas	9.8E+08	9.2E+09	8.2E+09
Uranium	1.7E+09	7.1E+10	6.9E+10
Hydropower	2.3E+09	2.3E+09	-
Wind	2.0E+06	2.0E+07	1.8E+07
Solid biomass and RDF	1.8E+08	4.4E+09	4.2E+09
Biogas	2.8E+06	1.0E+08	1.0E+08
Geothermal	1.7E+08	1.7E+08	1.9E+05
Solar photovoltaic	1.7E+05	1.7E+05	-
Solar thermal	8.2E+06	1.4E+07	5.5E+06
Total	**1.6E+10**	**2.2E+11**	**2.0E+11**



We also draw attention to the fact that low carbon fuels vary dramatically in water intensity. Wind and solar photovoltaic electricity demand almost no water. Geothermal, hydropower, and solar thermal electricity are over an order of magnitude more consumptively water intensive than natural gas-fired electricity, and liquid biofuels are over an order of magnitude more consumptively water intensive than oil-derived fuels (Fig. 4). For withdrawals, similarly, some low-carbon resources withdraw almost no water, while nuclear plants are extremely withdrawal-intensive. Indeed, delivered energy from coal and uranium is an order of magnitude more water intensive than any other resource, largely because of their use in power plants with once-through cooling systems. We note further that although this work does not consider important questions about local system stresses and contamination risks, unconventional oil and natural gas each have relatively low water intensity per unit of delivered energy compared to other fuel cycles (Figure 4). Current US energy trends suggest that volumetric water use for the energy system is likely to decrease, given expectations that wind, solar, and unconventional natural gas are likely to continue gaining market share[7].

Fig. 4. Quantitative summary of water consumption and withdrawal intensity per unit of delivered energy for US energy system, excluding nonconsumptive hydropower withdrawals, 2014 (see also Data File 1)

	Consumed, m^3/GJ delivered (2014)	Withdrawn, m^3/GJ delivered (2014)	Returned to source, m^3/GJ delivered (2014)
Water Source			
Ground	1.2E-01	1.7E-01	5.0E-02
Surface	1.1E-01	2.9E+00	2.8E+00
Reuse	4.4E-03	2.3E-02	1.9E-02
Total	**2.3E-01**	**3.1E+00**	**2.8E+00**
Water Quality			
Freshwater	1.9E-01	2.5E+00	2.3E+00
Brackish Water	6.8E-03	2.1E-01	2.0E-01
Saline	1.2E-02	3.1E-01	2.9E-01
Not RO Treatable	2.5E-02	4.6E-02	2.1E-02
Total	**2.3E-01**	**3.1E+00**	**2.8E+00**
Life Cycle Stage			
Production	1.4E-01	1.9E-01	4.4E-02
Processing	1.8E-03	1.2E-02	1.0E-02
Transport	3.3E-03	3.4E-03	1.2E-04
Conversion	7.5E-02	2.9E+00	2.8E+00
Post-conversion	5.2E-03	1.1E-03	-
Total	**2.3E-01**	**3.1E+00**	**2.9E+00**
Fuel Cycle			
Conventional oil	1.1E-01	2.8E-01	1.7E-01
Unconventional oil	3.5E-02	1.2E-01	8.1E-02
Ethanol	2.9E+00	3.5E+00	6.7E-01
Biodiesel	2.3E+00	2.9E+00	5.9E-01
Subbituminous coal	4.6E-01	2.2E+01	2.1E+01
Bituminous coal	4.1E-01	1.2E+01	1.2E+01
Lignite	5.4E-01	2.2E+01	2.2E+01
Conventional natural gas	5.9E-02	8.0E-01	7.4E-01
Unconventional natural gas	8.8E-02	8.3E-01	7.4E-01
Uranium	6.1E-01	2.6E+01	2.5E+01
Hydropower	2.6E+00	2.6E+00	-
Wind	3.2E-03	3.2E-02	2.8E-02
Solid biomass and RDF	1.4E-01	3.4E+00	3.2E+00
Biogas	4.6E-02	1.7E+00	1.7E+00
Geothermal	3.1E+00	3.1E+00	3.5E-03
Solar photovoltaic	1.9E-03	1.9E-03	-
Solar thermal	9.9E-01	1.6E+00	6.6E-01
Total	**2.3E-01**	**3.1E+00**	**2.8E+00**



This work's finding that about 10% of US water consumption is attributable to the energy sector (not including embodied water in the materials used to support it) is difficult to contextualize given the dearth of previous overall estimates, but it appears to be substantially higher than has been previously articulated. Given the dominance of power plant cooling systems for energy-related withdrawals, which are subject to mandatory annual federal reporting to the Energy Information Administration, withdrawals have historically been better understood. This work's withdrawal estimate is similar to the thermoelectric-only estimate made by USGS[74]. No studies known to the authors explicitly estimate the amount of water consumed by the US energy sector, but one recent study includes a limited subset of energy-related water-consuming activities that account for about 5% of its estimated total[70]. Thus, in addition to the much higher detail on national water consumption and withdrawal published in this study versus earlier efforts, this work suggests that water consumption for energy is higher than has been previously articulated. As is discussed further in the SI, however, the known limitation with the greatest influence on the estimate of the proportion of water dedicated to the energy system is that the total volume of water withdrawn and consumed in the United States as of 2014 is not precisely known.

Though this new set of estimates about water consumption and withdrawal for the energy system is an improvement over frequently old or nonexistent estimates, uncertainty remains inherently high given the lack of consistent water quantity reporting, definitions, and unit specification. In general, this work's absolute volume estimates are expected to be more reliable than its intensity numbers, for example because the denominators of the intensity estimates are not completely known (i.e., for total US water consumption) and because this single-year snapshot captures a static estimate for total water consumption that, in many cases, might not be a good reflection of intensities over time. For example, water withdrawals and consumption are not independent of precipitation, geology, market conditions, and other factors. Total volumes are expected to be more accurate than subtotals, particularly given that allocations across water source and water quality are often made based on general assumptions about the US water system. When water quality is not evident, this work conservatively overestimates freshwater contributions: given that use of non-freshwater resources is usually clearly identified, the default assumption that water is fresh is likely accurate. Specific uncertainties and assumptions associated with quantifying water withdrawal and consumption for the 126 processes included in Data File S1 can be found in the SI.

Future work will address some of the implications of this work's findings for water and energy co-management, regional differences, and planning, but the extreme challenge associated with generating even a single year snapshot of water use for energy warrants discussion of several fundamental sources of uncertainty and possible approaches to mitigating these uncertainties. That is, while this study improves understanding of the water-energy nexus as a major data update, it will itself become outdated, with limited ability to update or further refine values without redoing the study. This inability to continually reflect the energy system's water use is a major and pressing challenge for resource managers.

We specifically highlight three major challenges that contribute to uncertainty in understanding energy-related water use in the US: data collection and maintenance, definitions, and ambiguous units. These challenges are the roots of the most significant limitations to this work, namely data availability and confidence in the data that do exist.

Data collection and maintenance. The most serious challenge to a thorough understanding of water demands for the US energy system is a lack of consistently collected and maintained data. The energy industry includes vast numbers of facilities that, with a few important exceptions (e.g., thermal power plant operators), are not required to report water usage to any publicly available centralized repository. Outreach to operators for this work demonstrates that in many cases, operators do not measure or understand their own water demands, in some cases because they are not required to meter their water. As a result, any available existing data are frequently re-cited and transformed as "better-than-nothing," which obscures their age, context, assumptions, and applicability. For example, widely cited publications[3,81,83,89] rely heavily on an earlier compendium[80] that is itself largely based on a 1980 effort by the Department of Energy[79]. Even in 1980, the authors acknowledged weaknesses like data age, use of single-plant examples, and reliance on pre-operational estimates. Use of whatever data are available can be relatively unproblematic for thermodynamically driven processes like cooling or evaporation, where the relationship between known inputs and water use is well understood. In other cases, however, as with geologically-driven water demands at mines and wells, values vary dramatically by region and production method, even for similar fuels. Further, when industrial processes change, older estimates rapidly become obsolete.

To address this issue, we call for the creation of a standardized public repository of water data. We recommend that all major water users report at least annual water withdrawals and consumption to the federal government, as power plants and farms already do[30,90]. There are multiple potential approaches to creation of such a repository. For example, dedicated water data collection could proceed through an Energy Information Administration analog for water[91] or through an expanded USGS effort with metrics other than withdrawal, more frequent data collection, and higher industrial resolution. Alternatively, sector-specific organizations like the Department of Energy, the US Department of Agriculture, and others could collect centrally standardized data for their specific sectors by adding water resources questions to existing data collection efforts, and these data could be centrally aggregated by a cross-sector agency. Though a non-governmental organization could also maintain such a repository, we suggest that a federal effort would be preferred for three main reasons: to reduce data collection burdens on respondent facilities, given that they already provide other data to the government; to improve internal consistency with other major data products; and to provide higher assurance of longevity, archiving, and public access. The federal government maintains a wide variety of datasets on natural resources and the economy, recognizing their broad value, and we argue that existing information on water resources is insufficiently detailed.

Definitions. A second challenge is that core concepts related to water quantity assessments are inconsistent (and inconsistently applied) in the literature, in part because major organizations and standards disagree[74,87]. For example, "consumption" sometimes includes all water that is removed from its original source and not returned (as in this work), but sometimes specific processes such as interbasin transfer for water supply, discharge of groundwater to surface water, or coal mine dewatering are excluded. Similarly, "water" can mean freshwater or all water, and "use" is not always defined.

We recommend that academics, agencies, and other research organizations focus on harmonizing water usage terminology, with a focus not only on consistency but on representation of physical realities. Existing choices often seem to be justified by conflating concerns about water quantity and water quality, as when produced water volumes are excluded from assessment because the water is salty. Similarly, both hydropower and water-cooled thermoelectric power require removing water from a river, passing it through a pipe, and returning it, but thermoelectric withdrawals (which create thermal pollution) are tracked, and hydropower withdrawals are rarely defined as such (even in this work, we estimate hydropower withdrawals in the SI but refrain from including them in our overall estimate because of the way that national estimates are produced—including them would suggest that the US energy system accounts for 4000% of US water withdrawals, and quantifying the entire nation's water withdrawals to ensure definitional consistency is out of this work's scope). Consistent use of terminology reduces uncertainty when research draws on the literature, ultimately reducing the need for additional data collection and analysis.

Ambiguous units. A third challenge is that the research community frequently generates and publishes data with ambiguous units. Most difficult to overcome are the non-energy energy units commonly used in US settings, like "tons of coal" and "cubic feet of natural gas," which are problematic given that energy density varies even within fuel categories. When energy density is not specified, it is extremely difficult to re-analyze data in energy terms. Further, reports commonly fail to precisely define intensity units. For example, using units of cubic meters per gigajoule (m^3/GJ) requires careful explication of precisely which gigajoule is intended (e.g., primary versus secondary; produced versus delivered) and how the energy content is measured. This problem must be addressed to enable compatible reporting, but it is likely solvable without additional data collection, unlike the data collection and maintenance challenge.

Here, we recommend that academics, agencies, and other research organizations report energy units unambiguously. For example, research should rarely use unqualified energy units: a megawatt-hour at a power plant is not the same unit as a megawatt-hour sold to a residential user. Volume or mass units like million cubic feet or tons should not be reported without including energy densities.

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Supplementary Information.

Supplementary text (184 pages) describing methods by resource. Tables S1 to S15. Data file 1, including unit process data for 126 unit processes.

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Figure legends.

Fig 1. As of 2014, the US commercial energy system consumed an estimated 1.6×10^{10} m^3 of water per year, approximately 10% of total US water consumption. Figure shows water flows by water source (blues, at left), water quality (greens), life cycle stage (reds), and fuel cycle (color coded by energy resource per common industry practice) for 17 US fuel cycles. Flow widths are proportional to flows, and vertical widths sum to 1.6×10^{10} m^3 (i.e., total energy-related water consumption) across the figure. See SI for underlying data and more detail.

Fig 2. As of 2014, the US commercial energy system withdrew an estimated 2.2×10^{11} m^3 of water per year, approximately 40% of total US water consumption. This value excludes nonconsumptive hydropower withdrawals, estimated at 2×10^{13} m^3 (see SI for hydropower characterization). Figure shows water flows by water source (blues, at left), water quality (greens), life cycle stage (reds), and fuel cycle (color coded by energy resource per common industry practice) for 17 US fuel cycles. Flow widths are proportional to flows, and vertical widths sum to 2.2×10^{11} m^3 (i.e., total energy-related water withdrawals) across the figure. See SI for underlying data and more detail.

Fig 3. Absolute volumes for water consumption and withdrawal are depicted by water source, water quality, life cycle stage, and fuel cycle as described in this study. Nonconsumptive hydropower withdrawals are not included on the chart. Consumption plus return flow equals withdrawal. Pink bars under "conversion" represent subtypes of conversion activities and sum to the primary conversion values.

Fig 4. Intensity of water consumption and withdrawal per unit of energy delivered to the consumer (e.g., a kilowatt-hour in a home or a gallon of gasoline at a gas station) is depicted by water source, water quality, life cycle stage, and fuel cycle as described in this study. Nonconsumptive hydropower withdrawals are not included on the chart. Consumption plus return flow equals withdrawal. Data File 1 in the SI also includes intensities per unit of energy involved in a given process rather than per unit of delivered energy.