

A Critical Review on the Accounting of Energy in Virtual Water Trade

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Key Points:

- Virtual water of energy studies emphasize spatial and temporal impacts of burden shift from consumption to production
- Few studies focused on sub-annual variations in virtual water trade, limiting ability to couple with seasonal hydrologic variability
- While data are often overgeneralized, few studies capture data or methodological uncertainty in their results

Abstract

Virtual water trade analysis investigates the embedded volume of water associated with the movement of a good from production to consumption. Energy-derived virtual water trade includes electricity, fossil fuels, and other energy resources and their water footprints. This growing field aids in understanding competition for scarce resources and the burden shift from energy consumption to production. This review investigates recent trends in energy virtual water trade from 2007–2021. Through the review, we find several limitations of the current practice, including lack of inclusion of hydroelectric footprints, inconsistent definitions of water footprint, and varying methods of assessment. A majority of studies assessed virtual water trade at the annual scale, neglecting inter-annual variability, and were primarily focused on a few locations, such as China and the United States. We recommend that future studies improve understanding of sub-annual variability in virtual water trade, prioritize local empirical data to avoid data misappropriation, and characterize uncertainty to promote policy. Through this review of virtual water of energy research, we identify existing themes and propose future directions to facilitate enhanced utility of the methods.

1 Introduction

The concept of virtual water advanced water resources management and accounting research in the 1990s when Allan coined the term to describe and analyze the value of water embedded in food imports to the water-scarce Middle East (Allan, 1997). With this idea came new opportunities to understand how water-scarce regions could sustain themselves via the water embedded in imported and traded goods. Although virtual water research was originally applied to the trade of food goods between countries (Konar et al., 2011, 2012; Dalin et al., 2012), the concept has been extended to other traded goods and across many spatial scales. Notably, there is a rapidly expanding body of work specifically investigating the virtual water trade for energy. These studies coincide with greater emphasis on the energy-water nexus, a field that evaluates the interdependencies of energy and water resources (Gleick, 1994; Sanders, 2015). The energy-water nexus discusses the implications of energy demand for water abstraction and treatment (Sanders & Webber, 2012; Chini & Stillwell, 2017; Chini et al., 2021), the water required for primary fuel extraction and refinement (Mielke et al., 2010; E. Grubert & Sanders, 2018), and electricity generation (Macknick et al., 2012; R. A. Peer & Sanders, 2016, 2018). The energy-water nexus is a global area of concern with varying dependencies based on region and policy (Siddiqi & Anadon, 2011; Okadera et al., 2014). Hoekstra and Hung (2002) introduced the concept of water footprints in 2002, building off previous concepts of ecological footprints from the 1990s (Rees, 1992). The water demanded for energy resources is its water footprint, which, when paired with trade information, creates a virtual water trade network of energy. With the growing body of work, we see a need and opportunity for a systematic review of the state of the literature to evaluate the array of research methodologies and findings, discuss policy implications, and, importantly, identify gaps in analysis or understanding for future work.

The virtual water cycle is powered by trade and energy sources for transport, and it is necessary in understanding the full global water cycle (D’Odorico et al., 2019), especially as it interacts with humans (Sivapalan et al., 2014). The global virtual water trade of energy has significantly increased over the past decade, totaling 211 km³ in 2018 (R. A. Peer & Chini, 2020). D’Odorico et al. (2019) estimate total virtual water flows for all products are between 2300–3100 km³ each year. Therefore, the virtual water trade of energy represents 7–9% of the total virtual water cycle. A majority of the virtual water trade of energy comes from three sources: biodiesel, fuelwood, and oil (43%, 24%, and 22%, respectively) (R. A. Peer & Chini, 2020). The water embedded in country-to-country electricity trade is approximately 7.5% of the overall energy virtual water trade each year (14 km³ in 2018) (R. A. Peer & Chini, 2020), but the overall magnitude is in-

creasing due to greater number of interconnections and some regions showing increased water intensity of electricity (R. A. M. Peer & Chini, 2021). Virtual water trade of electricity also occurs within countries at large scales with estimates of 1–7 km³ per year between provinces in China (Gao et al., 2019; Liu et al., 2020) and 10 km³ per year between balancing authorities in the United States (Chini et al., 2018). An additional consideration for virtual water trade of electricity is that it is bounded by infrastructure. While the trade of other energy products and food is relatively unconstrained, the transfer of electricity is constrained by transmission lines.

Defining virtual water trade of energy facilitates understanding the burden shift of consumption to production of energy. Specifically, these burden shifts are relevant when energy is produced or refined in water scarce regions and then transported to other regions, burdening an already water-stressed environment with consumption that does not benefit the local community. For example, there are several studies that suggest a west-to-east shift of virtual water related to energy in China, where the west is already a water stressed location (Han et al., 2021; Zhu et al., 2015). Additionally, virtual water exports of electricity from the lower Colorado River, a heavily stressed basin, equal 8 times the direct water demand of the City of Phoenix, Arizona (Chini et al., 2018). Therefore, the accounting of embedded water within energy and its subsequent transport provides important context to the sustainability and environmental impact of energy supply.

The dynamics of energy-driven virtual water trade vary across multiple spatial and temporal scales. Geospatial scales of analysis range from sub-country, with watersheds, provinces, or infrastructure systems as nodes to global, with country-to-country trade. Additionally, studies include different energy sources in their estimates and analyses, creating a complex field of literature with minimal synthesis across its studies. Therefore, in this systematic review, we analyze the existing literature and present a comprehensive state of the field, recognizing its current extent and opportunities for enhanced growth. This review offers important insights to refine the analysis of virtual water trade of energy and its potential policy implications.

2 Systematic Review Methods

A systematic literature review on manuscripts published online before June 2021 yielded 69 relevant energy virtual water trade studies. Studies were first determined using a Scopus and Google Scholar boolean logic search with defined keywords for energy (energy, electric*, fuel, hydroelectric), water (water use, water consumption, water withdrawal, blue water, grey water, water scarcity, virtual water, indirect water, water footprint), and trade (trade, transfer, transmission, exchange). Studies from across the globe were included, but were limited to those available in English. The final criteria for articles included in the review was an explicit mention of the quantification of virtual water trade of energy with a presented value. Studies that included calculations of virtual water trade of multiple products aggregated together, without separating out energy were excluded.

Following an initial collection of several hundred results, the articles were first reviewed based on title and abstract, followed by the criteria above. The remaining 69 articles were read in detail and analyzed using a standardized form with specific questions regarding the study scale, scope, energy commodities analysed, data sources, assumptions, methods, and study context. This process created substantial metadata for each study that are summarized and analyzed in the remaining sections. The standardized form and accompanying data for each of the articles are provided in the supporting information.

3 Study Characteristics

3.1 Scale and Location of Analyses

Each article was divided based on three categories in the initial review: geographic scale, location of study, and temporal scale. Using these results, we plotted the 69 studies on a temporal histogram to detail the breakdown of the literature (Figure 1). The 69 studies explicitly quantify the energy-driven virtual water trade of their specific area of interest. From this figure, there are three clear outcomes: (i) studies on China dominate the literature, (ii) intra-annual studies are rare, and (iii) studies often focus on geopolitical boundaries.

Of the 69 identified articles, 47 (nearly 70%) of the articles investigated China; see Figure 1. Additionally, a bulk of these articles (28) focused on the provincial or regional boundaries within China as the nodes of the network. Largely, these studies all utilized the same data either from the China Statistical Yearbook or multi-regional input-output tables (MRIO). These studies identified the concerning trend of increasing virtual water trade from water-scarce provinces to water-rich provinces, or a general west-to-east flow. The prevalence of data represent an opportunity for robust analyses of China. However, there are concerns about the uncertainty and varying results of these studies using similar methods; see Section 5. Many of these studies in China lack a robust discussion on their assessments relative to existing provincial or regional analyses. As we seek to advance the field and use the results for joint management of water and energy resources, it is important that studies expand geographically and emphasise the contribution and any discrepancies in outcomes relative to existing works.

Of the remaining articles, only the United States (9) and Europe (4) were represented by multiple studies. Two studies were conducted on countries other than China, the United States, and European countries: Thailand (Okadera et al., 2016) and Australia (Lenzen, 2009). We speculate that the prevalence of studies in these three locations are most likely due to available data, active regional researchers, energy-water nexus policy and funding, among other reasons. Researchers in the area of energy, water, and virtual water trade need to further investigate and push for data in lower researched areas. Particularly, virtual water trade studies should focus on areas that juxtapose water scarce and water abundant areas, where increased virtual water trade could impact overall water security.

From a temporal perspective, there were very few studies that investigated sub-annual virtual water trade (3 studies); Figure 1. Multi-year and single-year investigations were the predominant time-scale of analysis. The lack of sub-annual studies is particularly relevant considering the seasonal nature of both water resources availability and energy demand. While investigations at this scale are limited based on data availability, studies of electricity virtual water trade have shown that both the trade of electricity and water intensity of production vary within the year (Chini & Stillwell, 2020; Chini et al., 2020). An aggregation to the annual scale misses variations in both seasonal water footprints and seasonal variability in energy trade. Additionally, the hydrologic cycle varies seasonally, resulting in varying impacts from virtual water trade throughout the year (Chini & Delorit, 2021). The impacts of these assumptions can also be found in studies that incorporated water scarcity. A total of 21 studies included water scarcity in their virtual water trade formulation; however, none did so at the sub-annual scale. These studies of water scarcity often utilized static water scarcity factors ignoring the sub-annual fluctuations of hydrologic indicators. As a result, there is a significant amount of uncertainty associated with annual or multi-year assessments of virtual water trade and studies that focus on water scarcity. Future investigations should take these intra-annual variations into consideration, especially when translating virtual water trade to policy and management decisions.

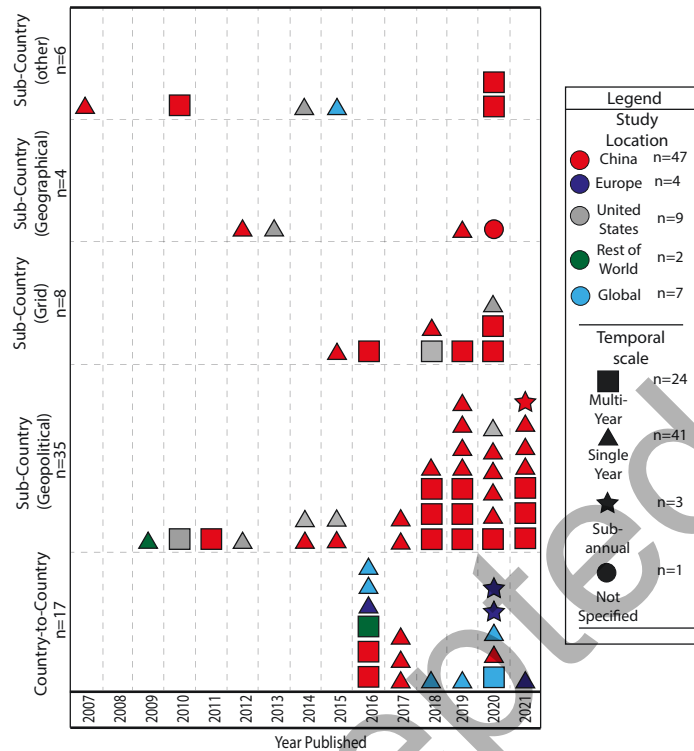


Figure 1. A majority of energy virtual water trade studies occur in China at the provincial scale at the annual or multi-year scale. Relatively few studies investigate sub-annual trends in virtual water trade. A total of 69 articles published between 2007 to Summer 2021 were evaluated in this review.

The final observation from Figure 1 is the focus on geopolitical boundaries such as provinces or states and countries. In comparison, only 12 studies investigated virtual water trade related to either electrical grid infrastructure boundaries or geographical watershed boundaries. While geopolitical grid infrastructure offer opportunities from a regulatory or data availability sense, they might not represent an adequate scale to understand the impacts of infrastructure or local hydrologic boundaries. For example, the virtual water trade of energy for the Yellow River Basin in China (Feng et al., 2012) and the Colorado River Basin in the United States (Kelley & Pasqualetti, 2013) were evaluated. These focused studies of stressed basins enable understanding of virtual inter-basin transfers that are important for long-term planning of basin water resources. Additionally, investigations at the electricity infrastructure scale (e.g., the balancing authority scale in the United States) provide insights into the virtual water outcomes of electric grid operations and transmission decisions (Chini et al., 2018). Therefore, it is important to investigate studies at an increased spatial resolution relative to the policy and decision goals of the analysis.

3.2 Energy Scope of Studies

Additional analysis investigated the type of energy and the corresponding water footprint assessed in each study; see Figure 2. Electricity was the predominant energy resource investigated in virtual water trade in 61 of the 69 studies (88%). Fossil fuels (coal, natural gas, and oil) were jointly assessed in roughly 40% of all studies, denoted by the bar graph in the top left of Figure 2. The combination of electricity and the three fossil fuels was the most common combination of energy sources studied. However, there were only 3 studies that provided a comprehensive look across all catalogued energy sources. Biofuels, such as biodiesel or ethanol, and biomass, such as firewood, were studied in less than 10% of analyses.

Interestingly, these proportions of energy sources are somewhat inversely related to their relative contributions to total virtual water trade of energy at a global scale (R. A. Peer & Chini, 2020). Biofuels and biomass comprise the largest proportions of total virtual water trade, whereas electricity accounts for approximately 7.5% of the global total. However, at higher spatial resolution, it is expected that the impacts of electricity virtual water trade would increase (Chini et al., 2018).

Another interesting observation is the focus on the blue water footprint over green and grey water footprints. Electricity, in particular, has a large grey water footprint based on thermal pollution from thermoelectric power plants (Chini et al., 2020). While green water footprints are relatively inconsequential for electricity and fossil fuels, they play a major role in biofuel and biomass production. Accounting for rainfall-based consumption as a green water footprint is essential for these energy sources (P. Gerbens-Leenes et al., 2012). Ultimately, a focus on the blue water footprint, neglecting green and grey water footprints, underestimates the virtual water impact of energy consumption and trade on the local environment.

4 Sub-Annual Investigations

A majority of virtual water trade studies of energy focus on accounting at an annual timescale. This timescale decision is largely driven by the trade and water footprint data that are available as singular (annual) values. However, it is important to note that water footprints of energy are not necessarily constant throughout the year (Chini et al., 2018, 2020). For example, water consumption for cooling can vary based on temperature of the water, which varies seasonally (Van Vliet et al., 2012). Additionally, hydroelectric generation water footprints vary based on evaporation from reservoirs (E. A. Grubert, 2016). Despite this variability, research often assumes static water footprints of energy production and generation. Regardless of the inclusion of seasonal water footprints, it is important to understand seasonal fluctuations of virtual water demand as water availability varies throughout the year based on local hydrologic cycles. For example, high virtual water trade that occurs in a season of lower water availability or drought has a greater impact on the water cycle than virtual water trade in a wetter season. This can be seen as the culmination of several factors: increased temperatures correlate with higher energy demands for space cooling, increased transmission losses, decreased water levels in hydropower reservoirs, and thermoelectric cooling efficiency losses due to high air and water temperatures and reduced water quantity (Mideksa & Kallbekken, 2010). Further, these limitations to thermoelectric cooling put power plants at increased risk of curtailment or shutdown (McCall et al., n.d.).

Therefore, it is surprising that only 3 of 69 studies (Figure 1) evaluated virtual water trade at a sub-annual time-scale. Two studies in Europe evaluate virtual water trade of electricity at the country scale and show variability in virtual import and export volumes monthly throughout the year (Chini & Stillwell, 2020; Roidt et al., 2020). Additionally, Jin et al. (2021) evaluated the net-virtual water trade between different regions

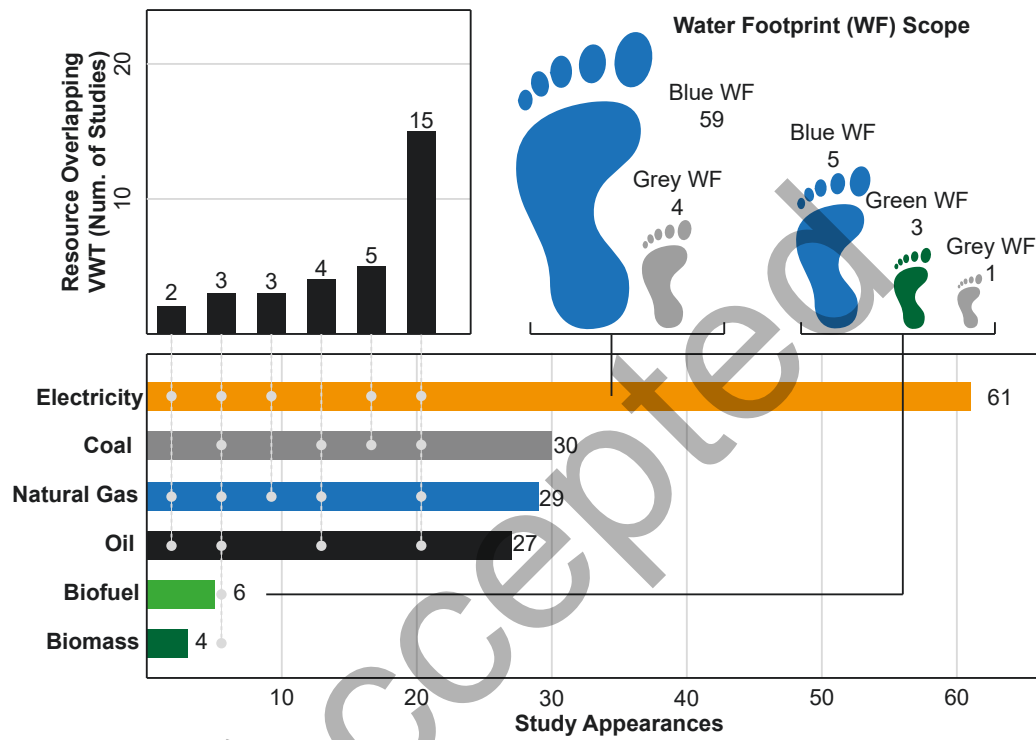


Figure 2. Electricity was the main energy source included in virtual water studies. Of the 69 studies, only 3 studies included the virtual water trade of all catalogued energy sources (top left). Additionally, while the blue water footprint was the predominant water footprint used in studies, only three of the six biofuel studies included green water footprints, which is a predominant component of these energy resources (W. Gerbens-Leenes et al., 2009).

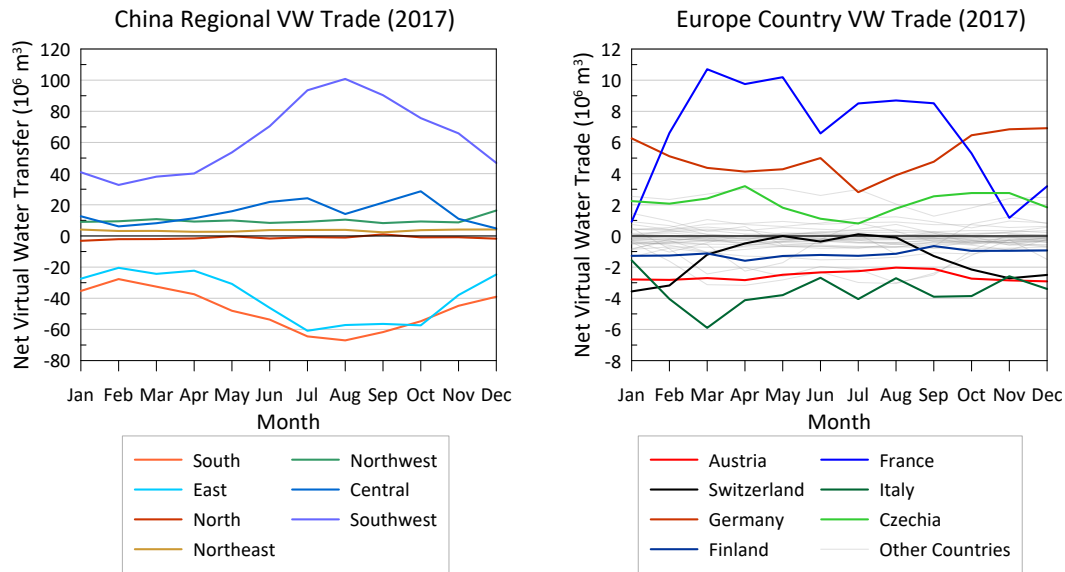


Figure 3. Monthly estimates of virtual water trade of electricity between Chinese regions (left) and European countries (right) illustrate how net virtual water trade varies within the year. A positive net virtual water trade indicates larger exports than imports. China monthly values are adapted from Jin et al. (2021) and Europe values are from Chini and Stillwell (2020).

of China and found variations at the seasonal scale. Figure 3 illustrates the varying patterns of net virtual water trade for electricity in regions of China and European countries. For example, Southwest China shows a higher export volume in the middle of the year, while East and South China show a large net import of virtual water during the same time period (Jin et al., 2021). Similarly, France is a high net exporter of virtual water resources from electricity during much of the year with lower net exports from November to January. Additionally, Switzerland is a net importer during the winter and fall seasons and is neutral in its net exports otherwise.

These type of studies illustrate with greater effect the impact of virtual water trade with natural hydrologic cycles and seasonal water availability. As a result, policy or adaptation measures can be implemented to account for these seasonal virtual water trade values and offset or mitigate against water scarcity. While these studies showcase the opportunities of intra-annual virtual water trade analyses, they are limited in their use of static water footprint values and their exclusion of water footprints for hydroelectric power (Chini & Stillwell, 2020; Jin et al., 2021). Additionally, these intra-annual studies focused on electrical energy, neglecting other sub-annual trends of energy production. These exclusions are juxtaposed against other studies which focused on the annual scale but included the water footprints of hydroelectricity, a large driver of water footprints for electricity (Liao et al., 2018; Y. Zhang, Fang, et al., 2020; R. A. Peer & Chini, 2020; Chini & Peer, 2021; R. A. M. Peer & Chini, 2021). While there are significant challenges to advancing sub-annual evaluations of virtual water trade, they are necessary in understanding trends and forecasting future water footprints (Chini & Delorit, 2021). In this light, future research should develop models that either use existing sub-annual data or disaggregate annual data based on energy consumption patterns, water temperature, or other means.

5 Uncertainty Quantification in Virtual Water Estimates

The final theme that arose from the review on virtual water trade was a lack of quantification of uncertainty surrounding estimates. Largely, the lack of uncertainty analysis can be attributed to the relative dearth and limited resolution of water footprint data at the local, regional, and national scales. However, there have been examples of how to implement uncertainty calculation using existing ranges of water footprints for energy both at the regional and global scales. For example, Chini et al. (2018) calculated uncertainty at an annual scale for virtual water footprints of electricity trade within the United States by incorporating monthly factors due to varying water footprints of production within the year. These factors were calculated for both blue and grey water footprints within the year with uncertainty captured by the 25th and 75th percentiles; Figure 4. Grey water footprints had a much higher uncertainty than blue water footprints of electricity for virtual water transfer between balancing authorities (Chini et al., 2018). At a global scale, R. A. Peer and Chini (2020) assessed the virtual water trade of multiple energy sources from 2012 to 2018 at the country-scale. Using published ranges of water footprints for the various energy sources, a projected range and median value of virtual water trade was calculated for combined blue and green water footprints (R. A. Peer & Chini, 2020). Comparing the two methods illustrates the relatively large differences in uncertainty associated with intra-national and international virtual water trade and the dominant impact of fuelwood and oil on overall uncertainty.

Through a synthesis of the literature, China was a well-established case study, specifically for virtual water trade of electricity at the interprovincial scale (Figure 1). However, there was minimal discussion of uncertainty associated with these estimates. As a result, the total volume of virtual water trade of electricity varied across multiple orders of magnitude for the same study area and time period; see Figure 5, which is based on 16 published studies for inter-provincial trade (C. Zhang & Anadon, 2014; Cai et al., 2017; C. Zhang et al., 2017; Liao et al., 2018; Gao et al., 2018; Y. Zhang et al., 2018; Gao et al., 2019; Y. Zhang, Fang, et al., 2020; C. Zhang et al., 2020; Y. Zhang, Hou, et al., 2020; Chen et al., 2019; Liao et al., 2019; Lin et al., 2019; Liu et al., 2020; Wang et al., 2020; Jin et al., 2021). While some of this variation can be attributed to the inclusion or exclusion of hydroelectricity contributions to virtual water trade, there was still a significant variation between estimates using a similar methodology, such as multi-regional input-output (MRIO) methods. Other opportunities for variance in the results include methodological boundary, water footprint selections, and inclusion of water source. While all studies generally indicate an upward trend in virtual water trade from 2000 to 2017 (the last year of available MRIO tables), there is an inconsistency in the total volume that is not captured via uncertainty or through comparison in the various studies. Despite the potential differences in method or approach, it is important that these studies capture uncertainty and reconcile with the differences in previous estimates to facilitate utility of the growing field of virtual water trade impacts.

6 Limitations of Current Practices

6.1 Approaches for assessing hydroelectric water use

Assessing the water consumption of hydroelectric facilities is widely known to be challenging due to the multi-use nature of hydropower dams and the influence of climatic factors on water consumption (i.e., evaporation) (E. A. Grubert, 2016; Bakken et al., 2017; M. Mekonnen & Hoekstra, 2012). Despite these challenges, the water footprint of hydroelectricity is known to have a non-negligible contribution to the water footprint of electricity (R. A. Peer & Chini, 2020; R. A. M. Peer & Chini, 2021). As such, one can argue that the exclusion of hydropower from water-for-energy studies that include electricity is a misrepresentation and likely underestimation of the water footprint. This mis-

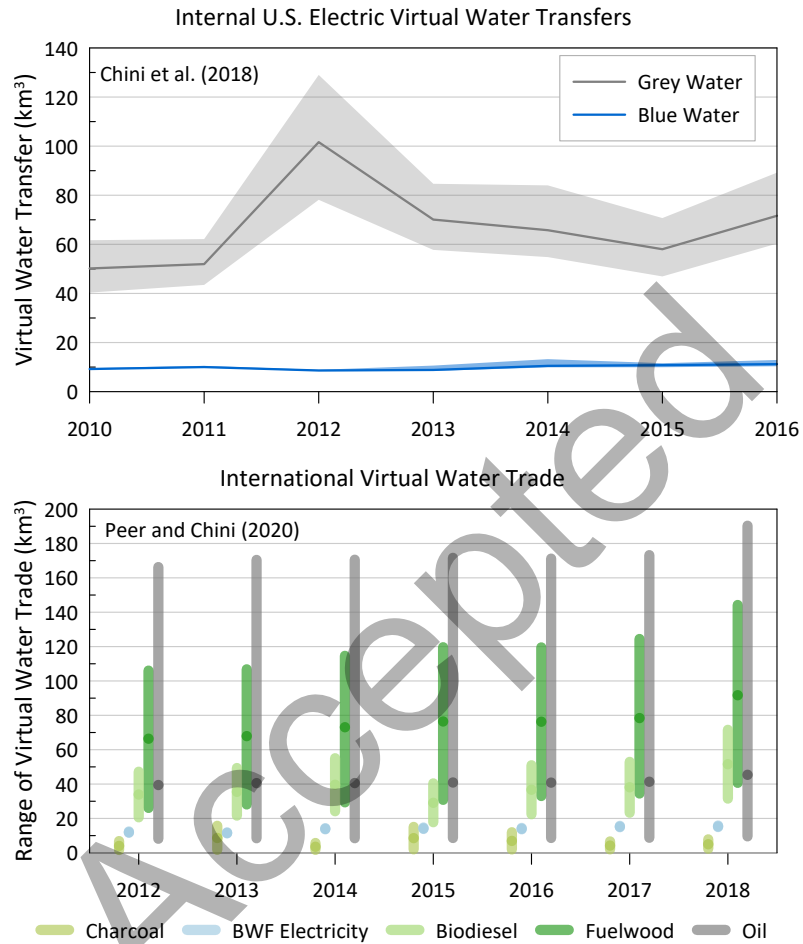


Figure 4. Estimation of uncertainty in virtual water trade studies provides important context for decision-makers. There is a relatively high uncertainty for grey water footprints of electricity compared to blue water footprints of electricity (top). However, compared to international energy trade, ranges of the water footprints for oil and fuelwood are the largest contributors of uncertainty (bottom).

Estimates of China's Interprovincial Electricity Virtual Water Trade

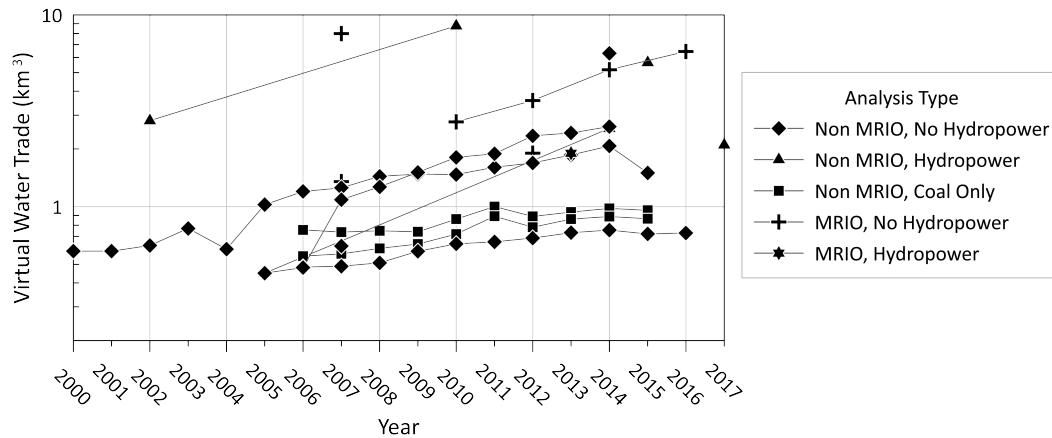


Figure 5. Estimates of virtual water trade of electricity between provinces in China vary by an order of magnitude across 16 unique studies of the country. Studies with multiple years of estimates are connected with a line, while single-year studies remain as individual points.

representation would be particularly pronounced in regions with significant hydroelectric generation (R. A. M. Peer & Chini, 2021).

Approximately half (34) of the studies reviewed here indicated that hydroelectricity was accounted for in their virtual water trade of energy studies. For all studies, the root source of the hydroelectric water footprint data was investigated (see SI for summary table). Most (70%) of these studies were completed for China. Just under half of the Chinese studies rely on annual data reported from the Chinese government (often cited as the “Statistical Yearbook” from the National Bureau of Statistics), which includes a broad category for electricity, but not an explicit account of hydroelectricity.

Seven of the studies that consider hydroelectricity in virtual water trade cite sources that trace historically, through a string of citations, to a 1992 study. In this study, Gleick (1992) evaluated evaporative losses as a function of surface area of the reservoirs, annual evaporative loss, and the average annual energy production of the facilities from almost 100 hydroelectric facilities in California and Pennsylvania, ranging in size from less than 1 MWe to nearly 500 MWe. Most of these studies citing Gleick (1992) are contemporary (i.e., as late as 2021) and assume, intentionally or unintentionally, that water footprint values for hydroelectricity as assessed in the early 1990s in the United States can be applied statically over time and across the globe. Using older data has been shown to overestimate the water footprint of energy substantially (E. Grubert et al., 2020). Additionally, the process of re-citation (and sometimes transformation) of older data creates ambiguity for the original source and applicability of these data, an issue that has been highlighted in other water-for-energy studies (E. Grubert et al., 2020; M. M. Mekonnen et al., 2015).

6.2 Definition of Water Footprint

Related to the issues described with hydroelectricity, the broad definition of water footprinting used creates confounding reports and results on the overall water impact of energy. Water footprints rely on estimates of consumptive uses of water as opposed to withdrawals. However, data and studies are not always specific about the distinction between these two sources. Water withdrawal refers to the amount of water removed from its original source (whether or not it is returned). Withdrawal, in the case

of thermoelectric power cooling, is orders of magnitude larger than consumption (Macknick et al., 2012; R. A. Peer et al., 2016; Diehl & Harris, 2014). As such, there is inconsistency in the application of the definition of virtual water footprint. In four of the analyzed studies, the authors explicitly state using water withdrawal data to calculate a virtual water footprint. An additional nine studies have unclear or unspecified water data sources, making it difficult to assess the quality and specificity of reported results.

Water withdrawal values contrast with the widely accepted definition for virtual water trade and water footprinting (Aldaya et al., 2012). Withdrawal volumes make little sense from a mass-balance perspective, given that this volume of water may or may not return to the original water source. Therefore, the use of withdrawal factors can severely overestimate the local impact of energy consumption on water resources. Instead, water withdrawal impacts should be assessed within the context of water scarcity concerns or through the lens of grey water trade (Aldaya et al., 2012; Chini et al., 2018, 2020). However, it is worth noting that data often are only available for withdrawal, leaving researchers to make assumptions as to the consumptive ratio of a given process.

6.3 Methods of Assessment

Jiang et al. (2015) identify four main methods to assess virtual water trade including life cycle analysis (LCA), inter-region input-output (IRIO) models, single-regional input-output (SRIO) models, and multiregional input-output (MRIO) models. Additional methods for embedded resource accounting include empirical and ecological network models (Ryan et al., 2016). One of the more common methods found in this study are MRIO models, specifically in China. Chinese MRIO tables include 31 territories/provinces and 42 sectors and are reported in economic value. All values within these tables are reported in units of 10,000 RMB. However, there is no consistent methodology to translate these values to energy, as economic value in the energy sector varies widely. These concerns potentially explain some of the large variation in assessments of virtual water trade in China; Figure 5. Despite the uncertain nature of these conversions, there was minimal reference to uncertainty or sensitivity in the final solutions for a majority of the articles reviewed within this study. Estimating virtual water flows using sector-wide water withdrawals and economic trade data introduces significant unquantified uncertainty and hinders accurate measurement or estimation of virtual water flows.

7 Implications and Future Direction

Virtual water trade analyses highlight the “burden shift” of water resources from production to consumption. Accounting of virtual water trade considers how trade of energy induces impacts on producing regions and the need to consider water implications in energy policy. Following a critical review of the literature, we identified three main areas of research needs. First, scales of analysis need to be refined both temporally and spatially. This refinement leads to the second and third areas focusing on data and uncertainty, respectively.

First, as mentioned previously, only three analyses occurred at the sub-annual scale: two in Europe and one in China. Therefore, there is substantial opportunity, as data allow, to create more refined estimates of virtual water trade that correlate to seasonal or sub-seasonal fluctuations in water availability. Refining temporal scale will both reduce uncertainty from annual analyses and create opportunities for targeted understanding and policy of energy and water interactions. In addition to temporal scale, there are a multitude of geographic scales used, with most analyses (35 of 69) at the sub-country geopolitical boundary. Future directions should seek to couple geographic boundaries with decision making to create best estimates of virtual water trade. Studies that work within grid (infrastructure) or watershed boundaries might have more appropriate applications

to understanding network vulnerability, while geopolitical boundary analysis might align stronger with policy decisions.

Data collection reveals information about priorities, as governments collect and publish valuable data for different purposes. China's creation of MRIO tables tracking inputs and outputs in currency illustrates an economic production focus. As such, adapting MRIO tables to water or other environmental material flows leverages existing priority data collection efforts, but also might introduce inappropriate error in converting currency to water volumes versus measuring/estimating water directly. Additionally, none of the MRIO tables include estimates of uncertainty. Conversely, direct water data (e.g., Energy Information Administration data from the United States) have their own challenges, including accuracy, but demonstrate value in the data collection efforts because many global studies apply U.S. specific values to other locations (Spang et al., 2014; Chini & Stillwell, 2020). Future efforts to understand the burden shift of water scarcity, for example, would benefit from local and regional water data that are specifically gathered to understand environmental impacts, not just economic concerns.

While refined data collection and scale will help better understand localized impacts, these efforts should not come without an understanding of uncertainty. Uncertainty in estimates originates from a few different sources. First, it is important that researchers know the chain of water footprint data, as outdated or geographically misappropriated data is common throughout the analyzed studies. These geographical mismatches have also been found in other areas of the energy-water nexus field (Chini et al., 2021). Also, there is a need to contextualize the results within the existing literature, specifically in heavily researched areas. Critical assessment is required to compare methods and resultant variations in outputs. For example, how are water consumption values calculated or included (e.g., cooling only, entire fuel life-cycle, net vs. gross)? And how do these values contribute to variation in outputs (E. A. Grubert et al., 2012; Meng et al., 2020; E. Grubert et al., 2020). Finally, as the energy sector shifts from fossil fuels to renewables, there is a potential for bias depending on the methods for water footprint assessment used, which should be accounted for within an uncertainty framework, especially considering hydropower, as previously discussed.

8 Conclusion

Our critical review of literature shows a rapid growth in the exploration of virtual water trade of energy. As energy transitions continue and the energy network becomes increasingly interconnected, it is important to understand both the spatial and temporal impacts of this burden shift between energy consumption and production. Additionally, as energy production transitions to sources with lesser operational impact, embedded impacts gain greater importance (E. Grubert & Zacarias, 2022). Water scarcity (M. M. Mekonnen & Hoekstra, 2016) and recurring droughts (Lubega & Stillwell, 2018) limit the water available to the energy sector, which could potentially have cascading impacts on energy trade. Specifically, with respect to electricity generation, lower streamflows reduce the amount of water available for cooling and hydroelectric production, while high temperatures reduce the efficiency of the thermal process. However, droughts and heat waves are rarely isolated and often are at the regional scale. Therefore, these events could not only hamper individual power plants, but also the ability to use power transmission or trade to alleviate a local power shortage (Van Vliet et al., 2016).

Interconnected energy systems have far-reaching implications where water stress in one location can lead to diminished supply in other locations. Virtual water trade of energy provides context in the broader hydrologic system with multiple sectors competing for limited water. The existing literature on energy-driven virtual water trade highlights important implications for energy and water resources. However, existing limitations of the research including annually-focused assessments, inconsistent methods, and

lack of reliable data in many regions impacts the ability for the field to grow. As energy systems become more interconnected, it is important to consider their wider impacts. Continuing to refine analysis of these embedded resources within the networked energy system supports a the development of more resilient systems and fosters sustainable joint energy and water decisions across the globe.

Data Availability Statement

Data were not used nor created for this research.

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