Science of the Total Environment 651 (2019) 2044–2058

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Water use in electricity generation for water-energy nexus analyses: The European case

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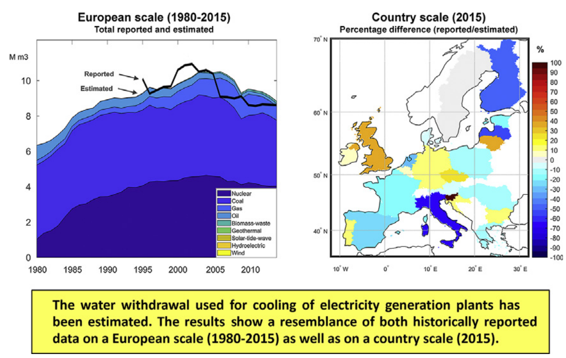
HIGHLIGHTS

- Electricity plant water withdrawals are estimated using a comprehensive analysis.
- Estimates resemble reported levels on spatio-temporal scales of country/year.
- The results support perspectives in larger scale water-energy nexus management.
- More open source, freely available and detailed data are however urged.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 June 2018
Received in revised form 2 October 2018
Accepted 3 October 2018
Available online 8 October 2018

Editor: Damia Barcelo

Keywords:
Water management
Water withdrawal
Water intensity factor
Energy systems
Europe
Large-scale water analysis

ABSTRACT

With almost 40% of the global population suffering from water scarcity, the need to manage water resources is evidently urgent. While water and energy systems are intrinsically linked, the availability of comprehensive, integrated data sets across the domains of water and energy is generally lacking. As a result, estimated indicators representing volumes of water usage per unit of electricity or fuel produced are often required to analyse the water-energy nexus. In this paper, an "ensemble" of indicators is assembled representing water usage spanning different electricity-generation technologies based on previously published works in an attempt to depict the level or lack of detail in current large-scale energy-sector water-usage data. Based on these, the degree in which using such estimates is suitable for reproducing electricity-production water-usage at coarser spatio-temporal scales is assessed. The performance of the ensemble median/min/max as a predictor of water use is evaluated for the period from 1980 to 2015 using additional information about the constituents of the European energy system. Comparing with the reported values for 1980–2015, the median provides a skillful reproduction of historical yearly water use for the EU (EU28) as a whole. A further analysis for 2015 indicates that reasonable agreement is also seen at the country level. Thus, the results suggest that an "ensemble-based approach" has the potential to provide sturdy estimates of yearly water use by energy systems for analyses at both the country and regional levels.

1. Introduction

Water and energy systems are inextricably interdependent. The water sector is a major consumer of energy for purposes such as water treatment, pumping and desalination. Similarly, water is essential for

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https://doi.org/10.1016/j.scitotenv.2018.10.045

cooling power plants, electricity generation and bio-fuel production, as well as in the extraction, mining, processing, refining and disposal of fossil-fuel residues. 44% of total global water withdrawals are used for energy production, a dominant share of which is cooling water in thermoelectric electricity generation (Collins et al., 2009). Energy and water are both limited resources that are essential for the fundamental services, including food production, required by a rapidly growing global population that is projected to reach 9.7 billion in 2050 (United Nations, 2017). As a result, it is increasingly critical to manage the nexus between energy and water properly (Kurian, 2017) in the broader context of dependent socio-economic sectors, including the wider water–energy–food nexus (Griggs et al., 2013; Howells and Rogner, 2014; United Nations General Assembly, 2015). Moreover, proper water-energy management is especially crucial in light of the fact that electricity and fuel production relies on an estimated 90% of non-sustainable water sources (WWAP, 2014), as well as the increasing demands for water, energy and food driven by, among others, the growth in population and economies (Hoekstra et al., 2012).

Over the last decade or so, analyzing issues within or related to the water–energy nexus has become increasingly important for both the scientific and policy-making communities (Dai et al., 2018; Miralles-Wilhelm, 2016). Likewise, the capacity to assess water and energy interlinkages at an increasingly higher resolution has also improved accordingly. Analyses of the water–energy nexus span a broad range of spatial levels, from the local (e.g. plant or city) (Chen and Chen, 2016) to the regional or national (Kibaroglu and Gürsoy, 2015; Mayor et al., 2015). Meanwhile temporalities range from multi-decadal (including climate change) (Mekonnen et al., 2016; Voisin et al., 2013) down to days or hours (or even lower) for operational applications (Castronuovo and Lopes, 2004).

A comprehensive review of methods and tools for macro-assessments of the water–energy nexus has recently been carried out by (Dai et al., 2018). From this analysis it is evident that, while a wide range of new methods and frameworks for comprehensively assessing interactions between water, energy and other elements have been developed, in general the availability of tools for nexus analyses that are at the same time integrative and multi-level is still poor (Daher and Mohtar, 2015; Howells et al., 2013). Instead, methodologies used for analyzing the water–energy nexus tend to be characterized by specific levels and data requirements (Liu et al., 2017), ranging from purely qualitative assessments to highly data-intensive model-based approaches (Granit et al., 2013). The review also found that none of the studies and methods considered provide a 'singular framework' for performing nexus studies.

The challenges of data availability at relevant spatio-temporal levels for analyzing the water–energy nexus, for example, on water use by energy systems and vice versa, is well documented (Chini and Stillwell, 2017; IRENA, 2015; Larsen et al., 2016). While in general water and energy systems can be considered to be well-monitored and managed (developing countries excluded), the availability of integrated data sets covering both domains is often severely limited at the relevant levels of aggregation in relation to nexus calculations, that is, beyond the site-specific level. Further, such data may be incomplete and inconsistent due, for example, to differences in the inherent conditions for the collection of data on water use by the energy sector between countries and regions, which can constrain the applicability and comparability of estimated water uses. For example, records from the US, while otherwise of good quality, have significant gaps concerning water-intensive energy technologies like nuclear (Macknick et al., 2012). Conversely, dependencies between water and energy systems, that is, water consumption or withdrawals related to specific energy technologies, may be expressed in terms of representative volumes of water use per unit (e.g. L/MWh) of electricity or fuel produced (Basheer and Elagib, 2018; Gleick, 1994; Inhaber, 2004; Macknick et al., 2012). This approach introduces a significant source of uncertainty arising from the (lack of) accuracy, but it also enables quantitative nexus calculations to be made at different levels and is frequently used by integrated assessment models.

In light of the poor data on water usage within the energy sector, as highlighted above, this paper addresses the extent to which reported estimates of water usage in electricity production provide an accurate 'bridge' when modelling the interdependencies between water and energy systems. Thus, many initiatives, like the Platform for Regional Integrated Modelling and Analysis (PRIMA) (Kraucunas et al., 2015), as well as the ETSAP-TIAM community (Føyn et al., 2011), aim at developing flexible multi-scale tools for analyzing the water–energy nexus in order to satisfy users' increasing demands by linking existing model components with new ones that use such an approach. In this context, the present study may be seen as an attempt to identify and validate a suitable set of parameters. To estimate water usage, multiple literature estimates of water withdrawal and consumption rates for electricity production technologies are collected in conjunction with the distribution of individual power plants and their corresponding technologies in order to calculate the country-level EU28 yearly water usages for 1980–2015, followed by a validation against reported numbers (Eurostat, 2018). The analysis is relevant because it highlights the best possible estimates of water usage within electricity production at coarser scales using freely available sources, albeit at coarse spatio-temporal resolutions (country/yearly). Thus, despite a certain resemblance between estimates and reported values, the paper also aims to show that the currently available data on energy-sector water usage is very inadequate, not least, in their detail and availability. Despite the current focus on providing open-access environmental data of increasing quality, data on the water–energy nexus are still limited in their availability. One aim of this paper is therefore to convey this information to users mainly in the academic community but also to politicians in light of the current tendency towards more open and available data.

2. Data and methodology

In this study, withdrawals of water are defined as the total amount of water that is extracted or diverted from its groundwater or surface water source and used during electricity-generation operations (as opposed to, e.g., including the construction phase), including the return flow. Thus, the cooling water addressed in this paper is freshwater only. Water consumption is similarly defined as the net balance, including only evaporated and transpired water, as well as water stored in crops and/or other products. Both terms (withdrawals and consumption) are jointly referred to as 'water usage'. Using this definition water consumption becomes a subset of water withdrawals.

The term 'median', as used in this study, is the most commonly used term in the recent literature (Davies et al., 2013; Macknick et al., 2012). It can therefore to some extent be regarded as the standard metric. However, some literature uses the term 'average' (Mielke et al., 2010; NETL, 2010), whereas other, typically older literature sources simply give a representative value (Gleick, 1994; Inhaber, 2004). Furthermore, many studies build upon each other by re-issuing the findings of older studies. However, for any literature sources where the median estimate is based the middle value in between the reported minimum and maximum spans, this may introduce a certain bias towards underestimation, as argued by (Macknick et al., 2012). The span of the entire range is addressed by employing the minimum and maximum estimates. Correspondingly, the estimated mean and min/max ranges cannot be asserted to be 'robust' from a strictly statistical perspective (e.g., as quantified by t-procedures).

2.1. Data

The data used in this study can be grouped into three main categories depending on their nature and how they are used. I) The first category covers data on the water withdrawal and consumption rates of electricity production as a function of the energy source and cooling