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Journal Article

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Publication date:
2024-05

Permanent link:
https://doi.org/10.3929/ethz-b-000670809

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Originally published in:
Smart Energy 14, https://doi.org/10.1016/j.segy.2024.100142

Smart Energy 14 (2024) 100142

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy

Water resiliency score – Is relying on freshwater to generate electricity a good idea?

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ARTICLE INFO

Keywords:
Water-energy nexus
Energy system resiliency
Renewable energy
Water stress
Water conservation
Water consumption

ABSTRACT

One commonly-used argument against fluctuating renewables is their unpredictability. In contrast, thermal power generation and hydropower are regularly presented as reliable and dispatchable. However, droughts and floods can render useless the share of the power generation infrastructure that directly depends on freshwater. In this work, the global power sector is analysed from an energy-water nexus perspective to evaluate its reliability in case of severe water scarcity on a per-power plant basis, proposing a new method for combining it with water stress scores. At a country level, known individual thermal and hydropower plants are paired with regional water stress projections from 2020 to 2030 and their water source as a bottom-up approach to account for the capacities at risk and identify the points where water dependence could render a power system unreliable. The results show that, globally, about 65 % of generating capacities are directly freshwater-dependent. Moreover, the share of capacities placed in the low-resiliency group increases from 9 % of the total installed in 2020 to over 24 % in 2030 in all scenarios. The findings could help guide the development of the global power sector towards a less water-dependent system and accelerate the deployment of low water-demand power generation technologies.

1. Introduction

Every report from the Intergovernmental Panel on Climate Change (IPCC) over the past several years has been consistent in their assessments, stressing the urgency of considerably reducing the carbon emissions from anthropogenic origin [1]. Moreover, the most carbon-intensive human activity is currently (and for the past few decades) power generation [2]. Therefore, the largest reduction in carbon emissions will be achieved by shifting towards low-carbon or carbon-neutral renewable energy sources (RES). Hence, energy system transition studies at different levels of geographical scope have become increasingly prevalent in the published literature, such as focusing on the post-COVID19 context [3], focusing on justice and environmental changes [4] and focusing on both transport and electricity [5], to mention a few. Some transition models are built around fossil fuel use with carbon capture and storage (CCS) [6], nuclear power [7], or entirely on RES [8]. Regardless of the core strategy of each transition model, there is generally a common assumption: hydropower and fossil thermal power are dispatchable and flexible [6], and nuclear power is a reliable, constant and uninterrupted power source optimal for baseline demand covering [7]. This is often mentioned in contrast with the daily and seasonal variability of solar and wind, usually portraying them as unreliable and inflexible [6].

However, the aforementioned assumption may be a faulty logic to start with. Climate change is also affecting the hydrological cycles [9], and freshwater is continuously decreasing its availability, more severely in some regions than in others [10]. The mention of water and freshwater is relevant due to the widely established energy-water nexus, which represents the mutual dependency of water and energy for human use [11]. There is a vast literature on water-energy nexus studies, with the term becoming commonly used around 2011 [12]. More recently, the term has been applied to the study of water dependence of specific regions such as Europe [13], Southern Africa [14], the Balkan peninsula [15], the Iberian peninsula [16], to name some. Furthermore, interdependencies of water and energy with other systems such as food [17], carbon [18], ecosystems [19] and climate [20] have also been explored.

Therefore, it has become evident that water and energy are deeply intertwined. Water is used directly for the production of electricity in hydropower plants, as a medium in steam turbines, ocean and geothermal power plants, while indirectly used for the production of

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https://doi.org/10.1016/j.segy.2024.100142
Received 21 December 2023; Received in revised form 28 March 2024; Accepted 11 April 2024

List of abbreviations

General abbreviations

NEF	New Energy Finance, energy system transition scenario by Bloomberg
CCS	Carbon capture and storage
CPI	Corruption perception index
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized cost of electricity
PV	Solar photovoltaic
RES	Renewable energy sources
WRI	World Resources Institute
UN	United Nations
MW, GW, TW	Megawatt, gigawatt, terawatt

Water resiliency score-related abbreviations

C_{XY}	Capacity of a coal power plant in country “X” and year “Y”
GO_{XY}	Capacity of a gas or oil power plant in country “X” and year “Y”
HP_{xy}	Capacity of a hydropower plant in country “X” and year “Y”
Kn	Total number of power plants with known location
n	Total number of power plants of a technology for country “X” and year “Y”
nk	Total number of power plants with unknown location
N_{XY}	Capacity of a nuclear power plant in country “X” and year “Y”
PPC_{XY}	Freshwater-vulnerable power plant capacity, in MW
RCR_{XY}	Relative capacities at risk, in percentage, of country “*X*” for year “Y”
TC_{XY}	Total active capacities of country “*X*” in year “Y”
$WACR_{Y}$	Global weighted average capacity at risk, in percentage, in year “Y”
WSS	Water stress score
WSS_{XY}	Weighted average water stress score of country “X” in year “Y”
WSS_{XY}^{local}	Local water stress score, specific for the power plant location in country “X” for year “Y”, data from WRI
WSS_{XY}^{avg}	Country’s average water stress score in year “Y”, data from WRI
WVC_{XY}	Total water-vulnerable capacities, in MW, in country “X” in year “Y”
X	Placeholder for country name
Y	Year

electricity in thermal power plants (for cooling purposes), or even the cleaning of solar panels [21]. Furthermore, in a future where hydrogen is posed to play a strong role in the global economic and power sector, hydrogen extracted from separating water into its base elements through electrolysis will further interlink water and energy. Likewise, energy is used in the transportation, treatment, heating and purification of water for human use.

Therefore, since water and energy are interdependent, disruptions in water availability can result directly in disruptions in power production. This was made evident in the summer of 2022, when a severe drought in central Europe disrupted the operation of several thermal power plants as well as supply chains and waterways [22]. Thus, continuing to assume the unwavering reliability of thermal and hydropower plants represents a risk to the stability of the power supply. In this regard, how to estimate what the risk is, assuming 100 % on-demand availability of thermal and hydropower plants?

Taking the abovementioned into account, there is a need for a bottom-up approach to evaluate all known water dependent capacities at a per power plant and at a global level. With the aforementioned in mind, this research work focuses on answering the following questions:

- Which capacities worldwide are vulnerable to shutdowns due to freshwater shortages?
- How to estimate the water-related risk for power plants?
- How does the geographical location of each power plant influence its risk factor?
- How is the risk factor likely to develop in the mid-term?

Hence, the presented article will explore a way to answer these questions and fill these knowledge gaps. The following sections will introduce the methods and calculations performed in this study, followed by results and their sensitivity analysis and will finish with a discussion and conclusion section.

2. Methods

The first step in this research work is to define freshwater dependency for the power sector. Although all types of power generation require water in one way or another, the scope of this research focuses exclusively on thermal power generated by coal, gas, oil and nuclear power, as well as hydropower. This is because power generation by new renewables like solar photovoltaic (PV) and wind requires an order of magnitude less water than fossil thermal generation [21]. Moreover, sources such as geothermal and concentrated solar, although significantly present in some regions, for the last couple of decades consistently generated less than 0.4 % of the electricity globally [23]. Fig. 1 is a flowchart representing in visual form the sources and combination steps for the method.

The base building block for this work has been established in Ref. [24], in which the location of all thermal power plants and their respective source of water for cooling purposes (as well as cooling systems) was presented in a comprehensive list. The abovementioned list also includes information on nameplate capacities, so a direct link between capacity and water source can be made. The other important building block is the water stress projections, as reported by the World Resources Institute (WRI) [25]. The water stress score (WSS), which is reported at both regional and country levels, ranges from 0 to 5, in which 5 represents the highest level of water stress and 0 represents non-existent water stress. In this scale, score 1 represents freshwater withdrawals by the local population and industry corresponding to 10% or less of the local available freshwater supply. Likewise, 2, 3, 4 and 5 represent withdrawals of up to 20 %, 40 %, 80 % and over 80 % respectively. WRI reports on the current WSS (for the year 2020) as well as provides pathways for its development in the future. The future projections of the WSS are reported for the years 2030, 2050 and 2080 in the form of three scenarios, naming Business-*as*-Usual (BAU), Optimistic (in this research work, it is referred to as Opt scenario), and Pessimistic (Pes) scenario. In this study, WSS projections for the years 2020 and 2030 from WRI [25] are used. The period of 2020–2030 is selected due to availability of data on a power plant basis.

In general, WSS are provided for individual countries as well as for individual provinces/microregions within each country. In order to capture the local effect of water availability or scarcity on the water resiliency of the country’s power sector, each specific power plant is matched with the corresponding province-level WSS from WRI [25], using the information regarding the power plant’s location in the power plant database. This step is especially relevant for the countries characterised by the large territory and/or by the wide difference in

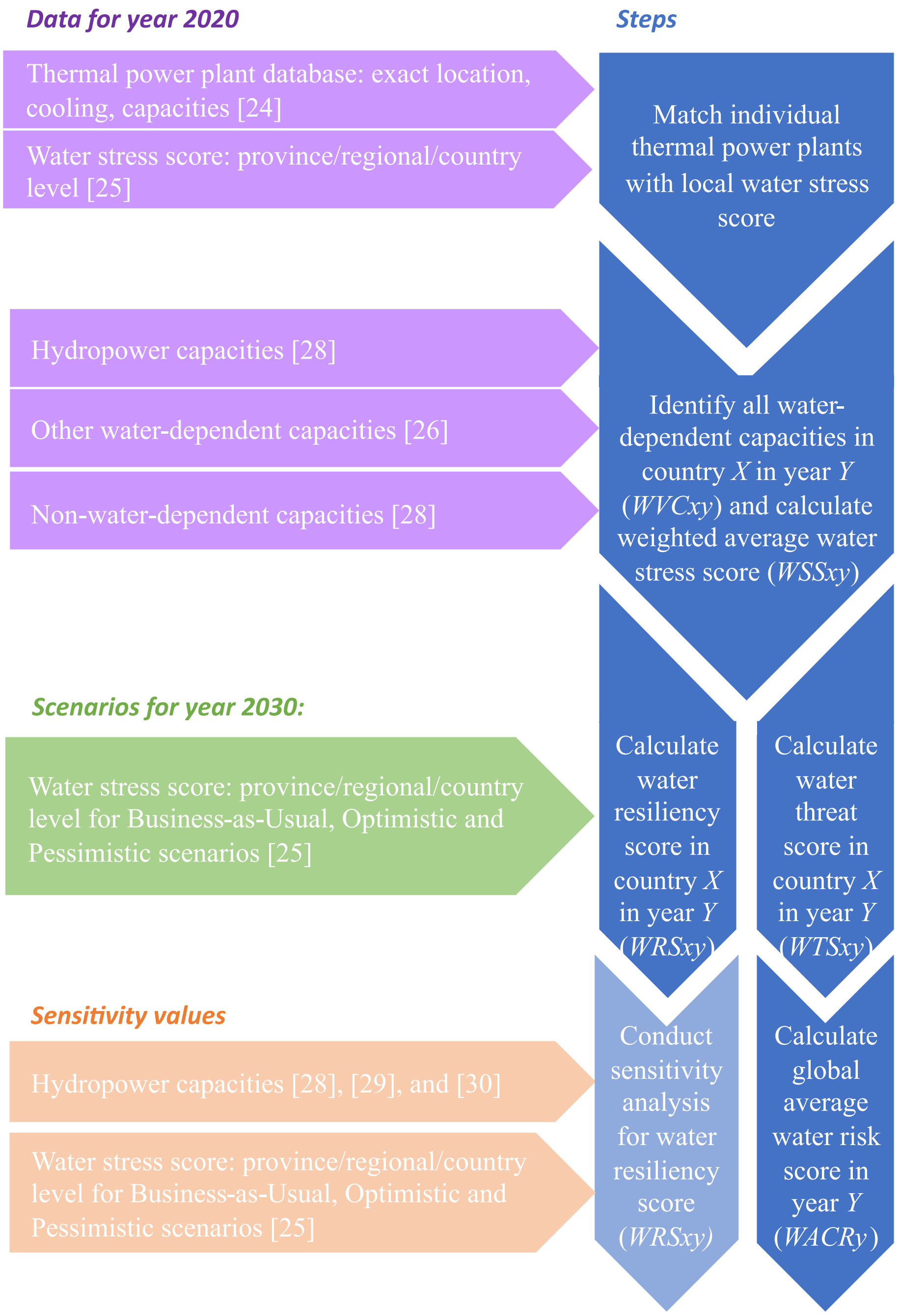

Fig. 1. Flow chart depicting the method and its sources.

freshwater availability within their territory.

After matching individual power plants with the corresponding WSS, the next step is to calculate the weighted average WSS observed in each specific country by its collective power plant fleet. This calculation ensures that the country-specific WSS, which will be used later in this study, accounts for the actual location of its power plant fleet and does not just demonstrate the general water risks observed in the country. The weighted average of each country's WSS is calculated using Equation (1).

$$\mathrm{WSS}_{\mathrm{XY}} = \frac{\sum_{1}^{\mathrm{kn}} \left(\mathrm{PPC}_{\mathrm{XY}} * \mathrm{WSS}_{\mathrm{XY}}^{\mathrm{local}}\right) + \sum_{1}^{\mathrm{nk}} \left(\mathrm{PPC}_{\mathrm{XY}} * \mathrm{WSS}_{\mathrm{XY}}^{\mathrm{avg}}\right)}{\sum_{1}^{\mathrm{n}} \mathrm{PPC}_{\mathrm{XY}}} \qquad (1)$$

In Equation (1), $\mathrm{WSS}_{\mathrm{XY}}$ denotes the weighted average water stress score of country "X" for year "Y", "n" is the total number of active power plants of country "X" which are freshwater dependent, and $\mathrm{PPC}_{\mathrm{XY}}$ stands for each power plant capacity. The numerator contains two parts: The first part with the index "kn" is for power plants which location is known, thus, it can be multiplied with the corresponding province-level water stress score WSS_{XY}^{local}. The second part of the numerator with the index "nk" is used in cases when the exact location of the power plant was not available in the power plant database (which mostly concerns future power capacities). In these cases, the country's average water stress score, WSS_{XY}^{avg}, is used. Finally, the reference values for capacities for thermal power plants at power plant level are obtained from Bloomberg New Energy Finance (Bloomberg NEF) [26] and Lohrmann et al. [27]. The data reported by the United Nations (UN) [28] is used as a source for total country capacities, which are used to validate the above-mentioned power capacities.

The main source for the hydropower capacities data is UN Data [28]. The authors acknowledge that the choice of the power plant data might considerably impact the results presented in this study. In order to analyse this potential impact, a sensitivity analysis is performed. The term $\sum_1^n PPC_{XY}$ from Equation (1) could be also referred to as the water-vulnerable capacities (WVC). For this work, they are defined as freshwater-dependent thermal power generation, plus all hydropower capacities. Therefore, the WVC are calculated using Equation (2), presented below.

$$\mathrm{WVC_{XY}} = \left\{ \sum_1^n \mathrm{HP_{XY}} + \sum_1^n \mathrm{C_{XY}} + \sum_1^n \mathrm{N_{XY}} + \sum_1^n \mathrm{GO_{XY}} \right\} \tag{2}$$

From Equation (2), $\mathrm{WVC_{XY}}$ represents the freshwater vulnerable capacities, in megawatts (MW) of the country “X” in year “Y”. $\mathrm{HP_{XY}}$ represents the hydropower capacity of each plant located in country “X” and year “Y” from first to last, thus “n” stands for the total number of power plants of each separate technology in the country. Therefore, “n” stands exclusively for the total number of power plants that are freshwater dependent for hydropower, coal, nuclear, gas and oil respectively. Likewise, $\mathrm{C_{XY}}$, $\mathrm{N_{XY}}$, and $\mathrm{GO_{XY}}$, stand respectively for the coal-fired, nuclear, gas and oil individual power plant capacities of country “X” and year “Y”. However, the abovementioned capacities that use freshwater for cooling, identified by Ref. [24], exclude the power plants that use seawater for cooling. The following step is to define, in relative terms, what is the share of vulnerable capacities of each country. The way to calculate this is presented in Equation (3) below.

$$\mathrm{RCR_{XY}} = \frac{\mathrm{WVC_{XY}}}{\mathrm{TC_{XY}}} \tag{3}$$

The total freshwater vulnerable capacities as well as their share in the country’s generation mix are presented in the Supplementary Material file. From Equation (3), $\mathrm{RCR_{XY}}$ stands for the relative capacities at risk, in percentage, of country “X” in year “Y”. In addition, $\mathrm{TC_{XY}}$ stands for the total active capacities of country “X” and year “Y” as reported in Ref. [22]. The next step is to take into account the water stress, thus generating the water resiliency score (WRS), which is then calculated using Equation (4), presented below.

$$\mathrm{WTS_{XY}} = \frac{\mathrm{RCR_{XY}} * \mathrm{WSS_{XY}}}{5} \tag{4}$$

$$\mathrm{WRS_{XY}} = \{1 - \mathrm{WTS_{XY}}\} \tag{5}$$

From Equation (4), $\mathrm{WTS_{XY}}$ represents the water threat score of country “X” at the reference year “Y”. In the case of the year 2030, the above-introduced scenarios Opt, BAU and Pes are considered. The dividend “5” is to normalize the WSS, originally from 0 to 5, into a 0 to 1 range. From Equation (5), $\mathrm{WRS_{XY}}$ stands for the water resiliency score of country “X” for the reference WSS at year “Y”. Therefore, the highest possible $\mathrm{WRS_{XY}}$ is 1, or 100 % resilient, can be obtained only if the country at reference does not have freshwater dependent capacities, or possesses a WSS of zero for the reference year. Finally, in order to understand the implications of WTS and WRS on a global scale, a global weighted average water risk score of the freshwater-dependent capacities is calculated using Equation (6), presented below.

$$\mathrm{WACR}_Y = \frac{\sum_1^n (\mathrm{WVC_{XY}} * \mathrm{WTS_{XY}})}{\sum_1^n \mathrm{WVC_{XY}}} \tag{6}$$

In Equation (6), $\mathrm{WACR_Y}$ stands for the weighted average capacity risk for year “Y” (from 0 to 1), and “n” stands for the total number of countries analysed. In this case, $\mathrm{WACR_Y}$ represents the average risk at which the global capacities stand, which is more representative than the average risk individual countries experience as countries with small capacities may have very good scores, thus skewing the perception of the real situation.

Finally, the last step of the analysis is to examine how the assumptions introduced in this study affect the calculated country-specific WRS values. Two parameters, which are identified to impact considerably the reported results, are Case Study 1 the WSS projections for 2030 and Case Study 2 the projections for the future hydropower development for 2030.

For the sensitivity analysis, the $\mathrm{WRS_{XY}}$ values are recalculated using the previously introduced equations (1)–(5) for the two aforementioned cases:

Case Study 1: $\sum_1^a \mathrm{HP_{XY}} = \mathrm{const}$ (from UN Data [28]) while $\mathrm{WSS_{XY}^{local}}$, $\mathrm{WSS_{XY}^{avg}} = \mathrm{var}$ (BAU or Opt or Pes scenarios from WRI [25]);

Case Study 2: $\mathrm{WSS_{XY}^{local}}, \mathrm{WSS_{XY}^{avg}} = \mathrm{const}$ (BAU scenario from WRI [25]) while $\sum_1^a \mathrm{HP_{XY}} = \mathrm{var}$ (UN Data [28] or IHA [29] or IRENA [30]).

As mentioned previously, WRI [25] presents three scenarios for the development of water stress globally: BAU, Opt, and Pes scenarios. While the BAU scenario is used to illustrate the country-specific results in the Results section of the article, two other scenarios are utilised as sensitivity values.

As for future hydropower development, different research institutions report different numbers for hydropower fleet in each specific county. While UN Data [28] is used to present the general results of this paper, for the sensitivity analysis, the numbers from the International Hydropower Association (IHA) [29] and the International Renewable Energy Agency (IRENA) are introduced [30]. The results of this analysis are presented in the “Sensitivity analysis” section of this study.

3. Results

In order to facilitate the communication of the results, the WRS scores are categorized for their analysis within one of three categories: high resiliency, moderate resiliency and low resiliency. At first glance, the country distribution of resilience appears positive, as shown in Table 1, with the number of countries, out of a total of 141 countries, and their percentage of the total in brackets. Defining countries’ energy resilience as high if they score over 90 % resilience score results in between around 26 % and 33 % of the countries analysed as highly resilient for water stress levels of 2020 and 2030 different scenarios. Moderate resiliency is subsequently defined as having a score between 60 % and 90 % resiliency. Globally, between about 45 % and 50 % of the countries score moderate resiliency for water stress levels in 2020 and 2030, according to all analysed scenarios. Finally, low resiliency is considered as scoring less than 60 % of resiliency. Considering both water stress levels in 2020 and 2030 in different scenarios results in only around 22 %–25 % of the countries at a low resiliency.

However, the abovementioned distribution is strongly affected by countries and territories with low capacities often tilting easily towards high resiliency or low resiliency, compared to more balanced and larger national power systems. When accounting for the capacities at different resiliency levels, the distribution dramatically changes. Globally, around 65 % of the total installed capacities is at some level of risk. Capacities within countries in the category of high resiliency add up to

Table 1
Distribution of the 141 countries according to their WRS, accounting for over 3.6 TW of freshwater dependent capacities. Outside the brackets is the number of countries and inside the brackets is their respective share of the total.

Scenario	Definition	2020	2030 Opt	2030 BAU	2030 Pes
High Resiliency	WRS >90 %	46 (32.6 %)	38 (27 %)	36 (25.5 %)	38 (27 %)
Moderate Resiliency	60 %< WRS <90 %	64 (45.4 %)	68 (48.2 %)	70 (49.6 %)	68 (48.2 %)
Low Resiliency	WRS <60 %	31 (22 %)	35 (24.8 %)	35 (24.8 %)	35 (24.8 %)

about 3 %–4 % of the total installed capacities globally for reference of 2020 and 2030 in different scenarios. Moderate resiliency capacities globally account for around 38 % and 52 % for reference years of 2020 and 2030 in different scenarios. In contrast, the added capacities of countries with low resiliency scores account for about 9 %–24 % for WSS reference levels of 2020 and 2030 for all scenarios. As a share of water-dependent capacities exclusively, around 5 % of the capacities are at high resiliency for all scenarios of 2020 and 2030, while around 58 %–80 % stand in moderate resiliency. In the case of low resiliency, it goes from around 14 % in 2020 to almost 38 % for all scenarios of 2030, as shown in Table 2.

Overall, the global water-dependent capacities stand at a $WACR_Y$ of over 29 % (moderate risk) for the reference year of 2020. However, for the reference scenarios of 2030, the WACR increases from 36 % to 37 %, barely avoiding the 40 % threshold to high risk. In other words, the average freshwater dependant thermal or hydropower plant in the world is currently at moderate risk, and that risk is expected to increase significantly by 2030, bordering the high-risk category.

For the individual countries, the development of WSS from 2020 to 2030 can be seen in Figs. 2 and 3 (for 2020 and BAU scenario of 2030, respectively). On the higher resiliency side, 48 and 36 to 38 countries score higher than 90 % WRS for reference scenarios of 2020 and 2030 respectively, of which 20 countries in 2020 and 13 to 16 countries for 2030 score more than 99 %, in their respective scenarios. However, most of these countries possess comparatively low capacities. The countries with the largest capacities within the high WRS category in 2030 are South Korea, Taiwan, Malaysia, Norway and Austria with 132.4, 69, 42.7, 39.2 and 27.4 GW (GW) of total installed capacities respectively, with WRS of about 91 %, 94 %, 96 %, 91 %, and 96 % for the reference scenarios of 2030 respectively.

In contrast, an increase from 31 to 35 countries score in the low resiliency bracket of WRS is expected from 2020 to 2030, out of which seven score resiliency lower than 30 % for the scenarios of both 2020 and 2030 and four score below 20 %, those being Syria, Kyrgyzstan, Botswana and Iraq. It can clearly be noticed that Kyrgyzstan and Botswana, both being coal-dependant and landlocked nations in high-water stress regions are those with the lowest WRS globally. Much like for the group of high WRS, most of the countries of lower WRS have relatively small power systems. However, this bracket includes some of the most power-intensive countries of the world. The countries with the higher total installed capacities within the low WRS group are the United States, India and Turkey with reported 1.3 TW (TW), and 435.1 and 99.2 GW, respectively. These countries get a WRS of 58 %, 43 % and 59 %, for 2020, respectively. These scores decrease to around 51 %, 52 % and 55 % by 2030 in Pes scenario, respectively. Together, the United States and India alone account for almost 1.4 TW of freshwater-dependent capacities.

The moderate resiliency bracket ranges from 64 to 70 countries for the reference scenarios of 2020 and 2030 respectively. The largest power systems within this bracket are China, Japan, Russia and Germany, with 2 TW, 375.2, 268.9 and 226 GW of total installed capacities respectively. These countries stand at WRS of around 61 %, 87 %, 71 % and 80 % for WRS reference scenarios of 2030, respectively.

4. Sensitivity analysis

The final step is to test the sensitivity of the assignment of WRS categories depending on the data used in this study. The main motivation to conduct this analysis is twofold: Firstly, WRI [25] reports three independent scenarios of the potential development of the WSS by the end of 2030. Secondly, some variation between the projections of the hydropower fleet development until 2030 can be observed in different literature sources for example, UN data [28], IHA [29] and IRENA [30].

Corresponding to the motivation of this analysis, the sensitivity analysis is conducted for two cases. In the first case study, the impact of the WSS scenarios for the year 2030 on the WRS is examined using the same source for hydropower projections – UN data [25] (as shown in Fig. 4A). In the second case study, the impact of hydropower development projections for the year 2030 on the WRS is examined using the same WSS scenario – BAU scenario from WRI [28] (as shown in Fig. 4B). Fig. 4 illustrates some examples of countries in Asia that differ in terms of their WRS values. The group of these countries is selected for visualisation due to the fact that there is a larger difference in the projections for hydropower development by 2030, compared to countries located in other regions. Thus, the impact of these assumptions on the calculated water resiliency score is more distinguishable and worth mentioning. The arrows demonstrate the projected development of the WRS in each specific country during the period from 2020 to 2030. The background colours of Fig. 4 correspond to the WRS category: high resiliency - green, moderate resiliency - yellow and low resiliency - red. As is evident from Fig. 4, many country-specific data points for the year 2030 overlap or the difference between the obtained scores is negligible. The largest difference in the obtained WRS values for 2030 (see Fig. 4B) appeared due to the difference in the hydropower development projections, while the WSS scenarios have a minor impact.

Moreover, it can be observed that only in a few cases (e.g., Bosnia and Herzegovina, Mozambique, Philippines, Sweden and Uganda) did the assigned WRS categories change due to the data change. Thus, it can be concluded that the sensitivity of the obtained WRS values is minor. A list of countries and their respective scores and capacities can be found in the Supplementary Material.

5. Discussion

It is clear that every human activity has a water impact. From agriculture [31], rare earth mineral recycling and mining [32] to even digital data usage [33] and digitalization [34], water and energy are integral parts of every human process. Even direct air carbon capture [35] which is often proposed as an option for combating climate change requires significant amounts of energy, and therefore water. Subsequently, shortages or disruptions in the supply of either energy or water can have dire consequences for the affected share of society. The interdependence of water and energy adds further layers of complexity to the system since in some cases, a shortage of water means an interruption in the supply of electricity, and vice versa.

The global power system is constantly changing, shifting focus from one mainstream technology to the next, in the past usually following economic and political prompts, and over the last few decades shifting towards a focus on reducing carbon emissions [36]. Moreover, energy transition pathways are constantly being developed to assist the decision-making in the federal and private investments in power infrastructure at a country level, in which a common practice is assuming full reliability in hydropower and thermal power generation for the balancing of power systems with high shares of renewables [37].

Table 2
Distribution of water-dependent capacities at different resiliency levels.

Scenario	As a percentage of total capacities				As a percentage of water-dependent capacities			
	2020	2030 Opt	2030 BAU	2030 Pes	2020	2030 Opt	2030 BAU	2030 Pes
High Resiliency	3.5 %	3.1 %	3.0 %	2.8 %	5.5 %	4.8 %	4.6 %	4.4 %
Moderate Resiliency	52.1 %	37.3 %	37.4 %	37.6 %	80.5 %	57.7 %	57.8 %	58.1 %
Low Resiliency	9.1 %	24.3 %	24.3 %	24.3 %	14.1 %	37.6 %	37.6 %	37.6 %

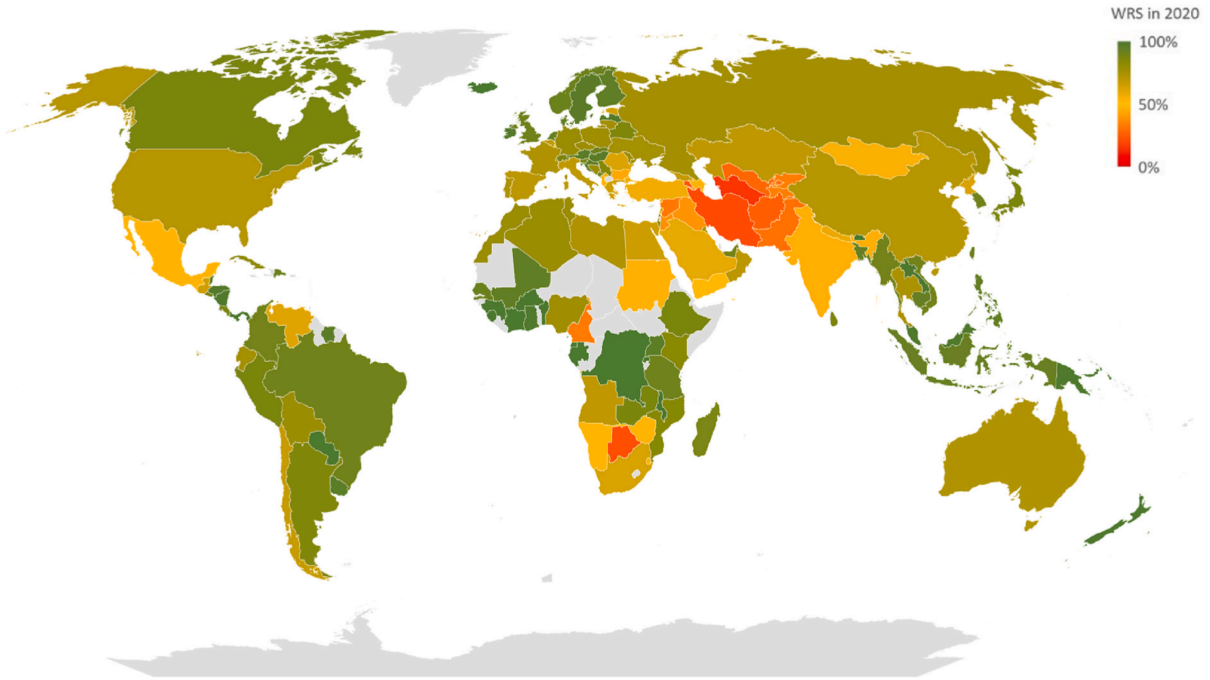

Fig. 2. WRS globally for the scenario of 2020 based on data from Refs. [25,28].

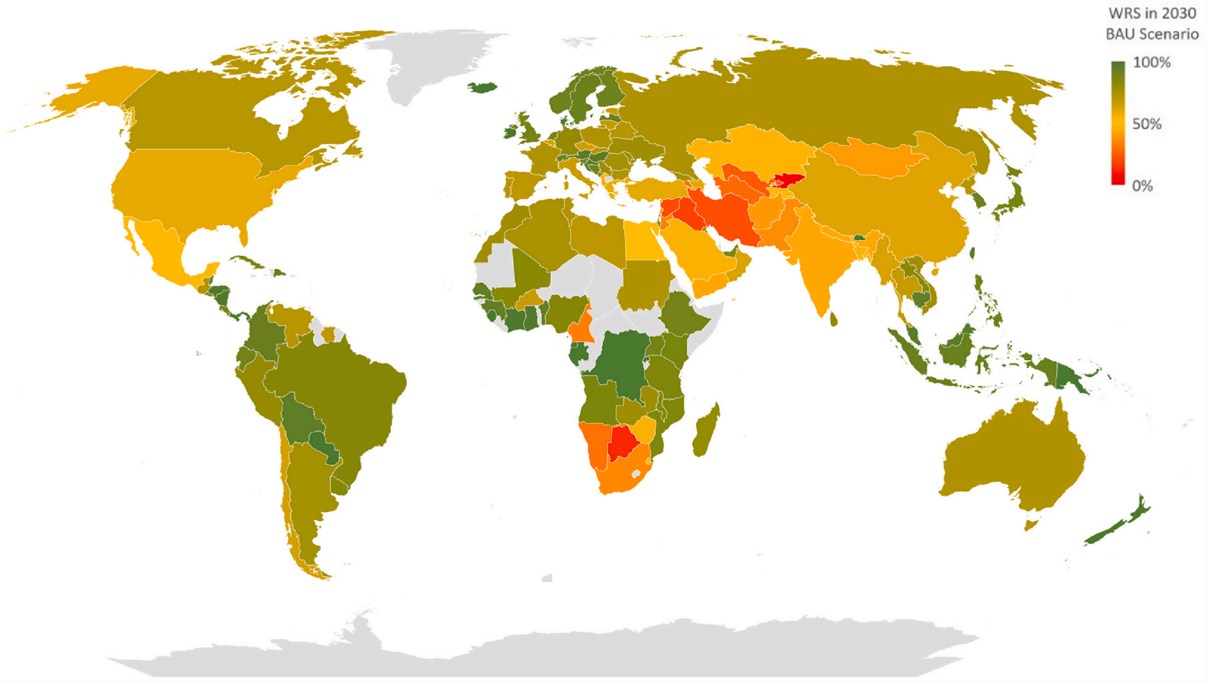

Fig. 3. WRS globally for the scenario of 2030 BAU based on data from Refs. [25,28].

Therefore, taking into account the risk associated with the assumption of absolute controllability over thermal and hydro power plants is an important consideration moving forward. However, power infrastructure is subject to risks beyond those of water shortage, such as terrorism, natural disasters, weather anomalies, and war [38]. A dire reminder of this unfolded in Ukraine when the Nova-Kakhovka dam was bombed on the June 6, 2023, simultaneously destroying a hydropower plant and taking away the main water supply for cooling of the Zaporizhzhia nuclear power plant [39]. Thus, accounting for the potential risks of every energy infrastructure project should go through additional risk assessment, both for the collective energy system and the individual power plant.

In addition, WRS appears to be a useful indicator for the status of the countries in other aspects. For example, the relation between WRS with the corruption perception index (CPI) [40] and electricity prices [41] are presented in Fig. 5 A and B, respectively. From Fig. 5 A, CPI is interpreted from 0 to 100 where 100 represents the least amount of corruption perception, and it can be seen that as WRS decreases the CPI also decreases, with only one country, Luxembourg, scoring higher than 60 CPI in the low resiliency bracket of less than 60 % WRS.

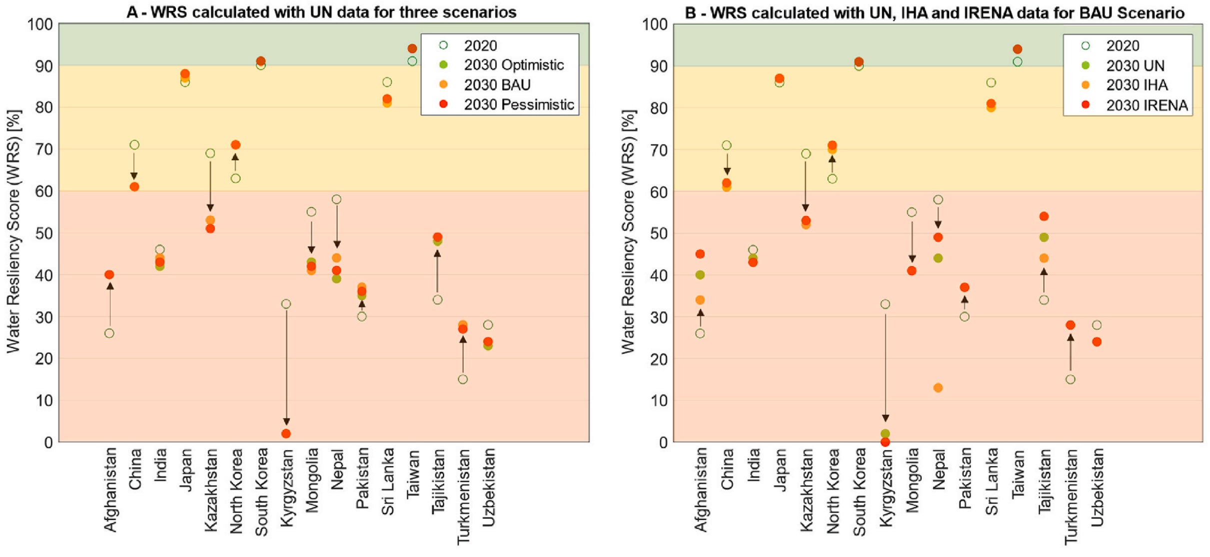

Fig. 4. Sensitivity analysis case studies (A) Case Study 1 and (B) Case Study 2.

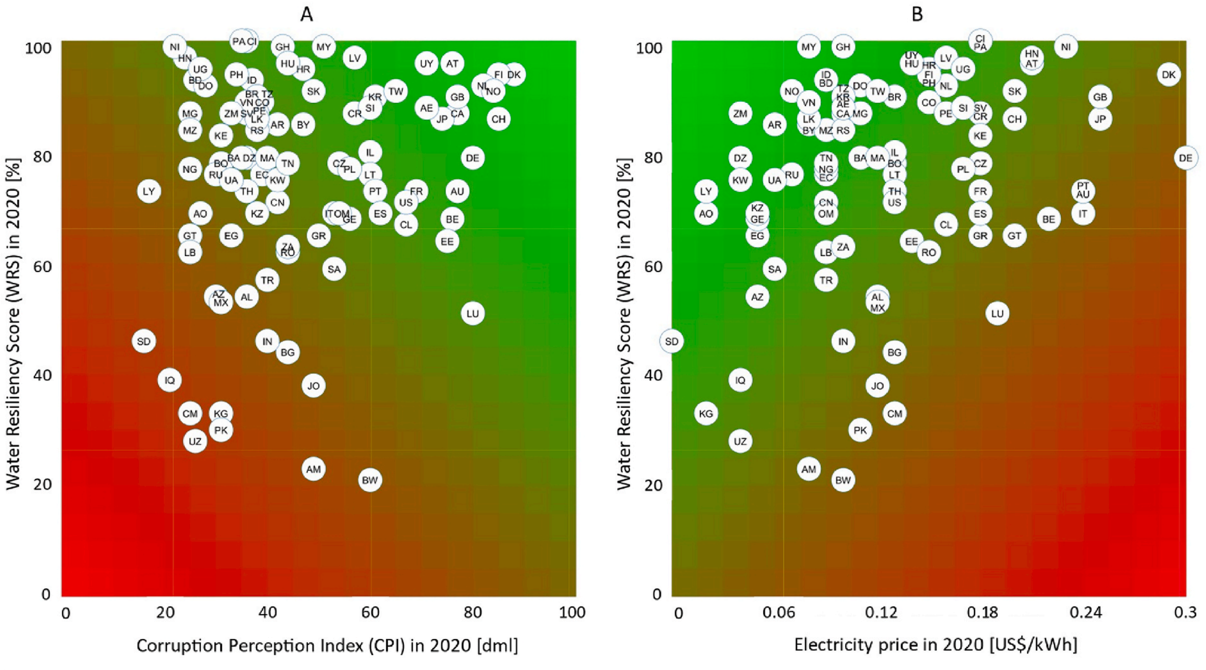

Fig. 5. Relation between WRS and CPI (A), and WRS and electricity prices (B) in 2020.

Similarly, WRS appears to be a metric related to the electricity price in the countries of the study. As the WRS increases, the price of electricity tends to also increase, with only one country in the low resiliency category experiencing a price higher than 15 USD/kWh. However, the relation is clearly not linear, as the increase of WRS groups the majority of countries in the top-left quarter, where the lowest prices and higher WRS. The authors acknowledge that more meaningful results might be obtained while analysing the relation between WRS and the country-specific values of the Levelized cost of electricity (LCOE). However, this data was not available for the analysis in this study.

Moreover, the Intergovernmental Panel on Climate Change (IPCC) assessment on water and climate change of 2022 [42] reports that energy related adaptations to water shortages would be rather effective globally (although for some regions more than others) and for all scenarios of global warming. In addition, the same report also highlights with high confidence that energy related adaptations to water scarcity could potentially have negligible or small residual negative impacts. The IPCC report [43] presents further supporting results, highlighting that inland thermal power plants are expected to contribute to localised water stress. Furthermore, adoption of CCS for carbon emissions mitigation of fossil-fuelled thermal power plants would considerably increase the demand for water among other things [44].

6. Conclusions

Globally, over 22 % of the countries and almost 38 % of the global capacities are found to score a low water resiliency status due to their freshwater dependence and vulnerability to water stress conditions at their location in 2030. The method proposed in this manuscript underscores the high vulnerability some countries are facing, and how difficult it would be to address it by presenting both in relative and absolute terms the capacities at risk. Only 4 countries scored a WRS lower than 20 % in 2030, Syria, Kyrgyzstan, Botswana and Iraq, as a result of a combined high WSS and also a high share of freshwater-dependent capacities. Moreover, the combined capacity of their power systems is around 58 GW, which is a significant size of the power system to correct, but far from the most problematic countries in the low resiliency bracket: the United States and India, with a combined freshwater-dependent capacity of almost 1.4 TW.

Therefore, water dependency and water resiliency should be part of the decision-making process for the energy transition, particularly in the abovementioned countries. Furthermore, the presented work highlights the importance of the consideration of water for the development of energy transition scenarios towards zero carbon emissions. Energy planning and management should go hand in hand with water planning and management as long as both strongly depend on each other, and specially at locations of severe water scarcity. Moreover, beyond water resiliency, curbing down water usage in the energy sector would logically result in higher water availability for other human activities, such as municipal water use or agriculture. Thus, increasing the water resiliency score of a power system could prove to bring benefits in addition to energy and security.

Freshwater dependency is something that can be estimated only at a power plant level based on a variety of factors. Therefore, conducting assessments that go far in the future, even using reputable energy transition models, is not possible using the approach presented in this study, as transition models tend to report total capacities and generation without assessing the optimal geographical distribution of the future power infrastructure. This condition limited the work to the data made available by Refs. [24,27] at a power plant level. A method for estimating future freshwater dependencies by the power infrastructure still needs to be developed. Moreover, the use of alternative transition models and forecasts for the total capacities would result in variations to the presented results. In addition, water stress scores obtained from Ref. [25] are used at the highest accuracy level available, which involves sub-regions within countries. However, variations in water stress and water stress projections within the sub-regions are likely to be present to certain degree. Until higher geographical accuracy for water stress is available, this will continue to be a limitation for the proposed approach. Furthermore, in almost all regions of the world there are significant seasonal hydrological variations, which is a significant limitation as the sources used for water stress scores only report year-round averages.

For the continuation of the work, linking the capacities with power generation through global and regional analysis could provide further insight into the potential power disruption risks and resiliency from the water perspective.

CRediT authorship contribution statement

Javier Farfan: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alena Lohrmann:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization. **Henrik Saxén:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2024.100142.

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