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A Review of the Water-Energy-Carbon Nexus for Environmental Sustainability

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Abstract

This study investigates the link between the water-energy-carbon nexus on the environment. The water-energy-carbon nexus, often known as the interdependence between water, energy, and carbon, is well acknowledged for its significance, and reviewing the advances in this nexus can help in identifying relevant tools for WEC management on sustainable development. Similar research in terms of energy intensity or other measures of resource use efficiency often characterizes the WEC nexus. The objective of this paper is to cross-examine various related papers on at least two of the three nexuses being discussed in this paper. Investigate their life cycle assessments and reactions concerning a sustainable environment. The synergies and trade-offs between the three aspects as an integrated whole have only been the subject of a small number of nexus investigations. This review shows that the primary constraints for sustainable development WEC nexus research may be vague system borders of a nexus and vague urban inner structures. In addition, the creation of a theoretical framework is suggested, and significant methodological advancements and future research areas are underlined as being urgently necessary for the urban WEC nexus

1. Introduction

Water, energy, and carbon are fundamental elements that determine how humans impact the environment [1]. According to reports, even in the most optimistic scenario, the world's energy requirements will increase by 30% between now and 2040, which is the equivalent of adding another China and India to the current level of demand [2].

Nearly all societal metabolic processes require water as it is a vital life support. By 2050, almost 75% of the world's population might experience a freshwater shortage [3]. Additionally, the significant impacts of global climate change are being exacerbated by carbon emissions from the combustion of fuels used to provide energy and clean water [4]. Even more complicated is the fact that the intricate networks of economic systems at all scales frequently have highly interconnected energy, water, and carbon flows [5]. Water is required for the generation of about 90% of all energy, and each year, 15% of the world's total water outflow is utilized for energy supply [6], while the production of water and the treatment of sewage both consume a significant amount of energy [7].

Several industries that are water-intensive like agriculture, food processing, and cement manufacture, also use a lot of energy and emit a lot of carbon. Researchers began to think about ways to resolve conflicts between energy and water after realizing that both resources can be extremely scarce.

Climate change mitigation, energy security, and water security are three of the most important current policy goals facing decision-makers, and these three goals are directly impacted by the water-energy-carbon nexus. Globally, it is estimated that energy production and consumption accounts for more than two-thirds of GHG emissions and with global population increase and escalating urban expansion increasing demands for energy, water resources, providing secure, affordable, and sustainable water and energy supplies is as critical to human survival as carbon reduction [8]. In the future decades, severe monthly temperatures are predicted to occur often even if emissions are lowered to representative concentration pathway (RCP) 2.6 levels [9]. The development of more countries and the urbanization of more cities are rapidly expanding both the volume of metabolism through increased resource extraction and their pollution emissions to ecosystems as a result of rapid urbanization and industrialization [10]. Unfortunately, these quick procedures have detrimental effects on the environment [11] like environmental pollution, resource depletion, and climate change which the United Nations environmental program identifies as challenges faced by the World. Thus, analyzing the water-energy-carbon emissions (WEC) nexus is important since it is essential for reducing environmental footprints, and striking a balance between water, energy, and climate is imperative for sustainable growth.

Two essential elements in the global quest for sustainable development are water and energy [12] in response to the Sustainable Development Goals of the United Nations. Consequently, the water-energy nexus is being discussed more and more in literature as a crucial topic for strategic policy planning and future sustainability planning [13], especially given that the two resources are particularly vulnerable to the effects of global climate change [14].

The security of energy and water resources as well as efforts to reduce carbon dioxide emissions are among the many environmental issues that most urban areas face. Metropolitan cities, for instance, account for 67% to 76% of worldwide energy use [15] and the impact it has is anticipated to keep increasing during the ensuing decades as a result of processes of global urbanization [16, 17]. Cities are significant contributors to water pollution and account for 70% to 80% of worldwide CO_2 emissions [18]. More significantly, as can be shown below in Fig. 1 (WEC) are tightly related to one another via the product supply networks of the cities. For example, large volumes of water resources are needed to supply cities with energy continuously such as coal mining and thermoelectric power generation [19, 20], and a lot of energy is needed to build and run urban water infrastructures such as pumps and water purification systems [21, 22] worldwide CH_4 emissions are a result of both urban wastewater treatment and energy consumption by cities, which together account for a significant portion of worldwide CO_2 emissions. Water scarcity, the production of power, and urban energy use may all be impacted by global warming brought on by CO_2 emissions. To find overall benefits and prevent unexpected consequences, sustainable WEC management of cities must be assessed through the lens of the WEC nexus.

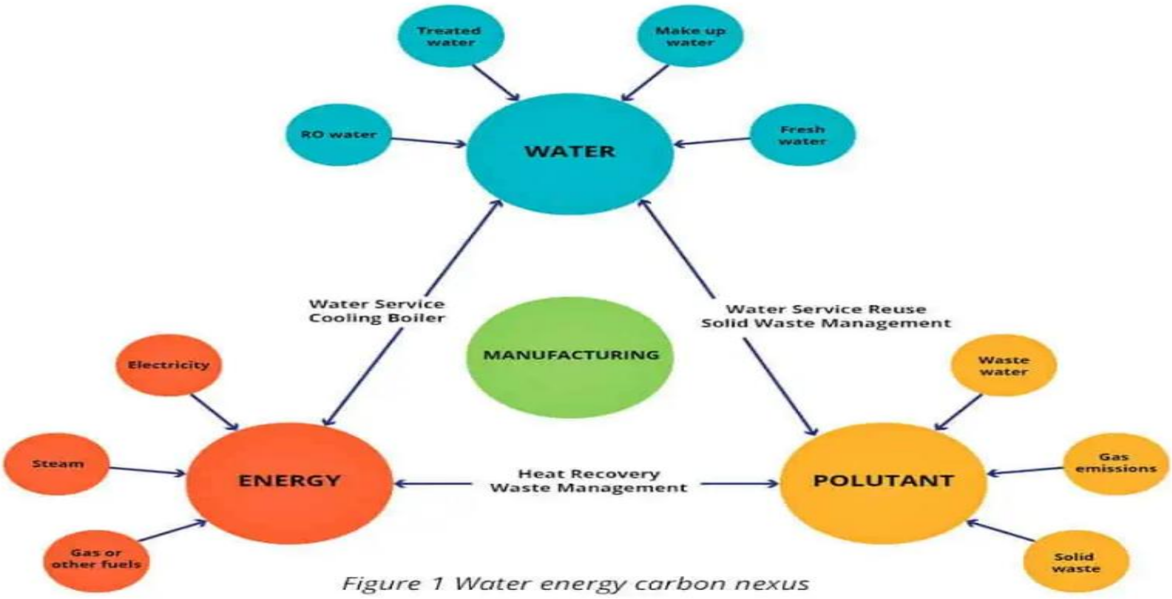

Figure 1: Water Energy Carbon nexus, 2022. (Source: Wasmer, 2022: online) [23]

2. Water-Energy Nexus (WEN)

Several papers have extensively studied how energy and water interact. The WEN is the unbreakable connection between water and energy. The phrase encompasses all facets of water and energy interactions, including both "energy for water" and "water for energy" scenarios. Energy is utilized in several processes for delivering, purifying, and using water. Water is a crucial component in the production of energy (cooling, hydroelectric power, some fossil fuel extraction, and increasingly, biofuels). On a fundamental level, water is needed for electricity generation, and electricity is needed for both water purification and transportation. Many assume that neither water nor electricity poses a threat to either security of supply, there has historically been little incentive to understand the nature of these connections [24]. This assumption is now being contested as the connections between water and energy are coming into sharp light in previously unheard-of ways due to industry reforms, rising demand, and more lately, climate change.

2.1 Water demand of energy systems

To produce electricity in 2010, 583 billion cubic meters of water were taken (about 15% of the total water withdrawal worldwide), and 66 billion cubic meters were finally consumed [25]. The world over, only agricultural irrigation requires more volume of water than energy production [26]. A humongous volume of water is required for the life cycle of energy production, the drilling and fracturing procedures used in oil and gas exploration heavily rely on water [27, 28]. Thermal power generation makes use of a lot of cooling water [29]. Cleaner forms of energy also require water for production. The processes used in mining to collect and process fuels, cool equipment, and prevent dust all require water [30].

2.2. Water demand for fuel production

2.2.1 Non-Renewables Energy

Water is required during the lifecycle of producing various forms of fossil fuels. Mining for coal is possible both above and below ground. Around 60% of the world's coal is mined underground, where the water use ranges from 70 - 260 million gallons per day in the USA [31] and following mining, coal undergoes cleaning, beneficiation, and thermal processing procedures to separate coal of varying grades and enhance the fuel's thermal performance.

A method known as hydraulic fracturing is deployed in the production of natural gas and shale oil as water and addictive are injected into the ground to fracture rocks and produce pores and fissures in the surrounding rocks [32]. In the life cycle assessment of crude oil production to produce 1 barrel of crude oil, 1.71 to 8.25 barrels of fresh water are used, and depending on the method up to 2.4 to 9.51 barrels are withdrawn to produce 1 barrel of conventional crude oil [33]. Aside from the intensive consumption of water for the extraction of crude oil, the same process is one of the leading causes of pollution swallowing groundwater and surface water [34].

2.2.2 Renewables Energy
The most popular form of renewable energy is bioenergy, which is produced from non-fossilized materials [35] and it is produced from various types of biomasses mainly decayed plants, animals, wastes from households and industries and transformed into sources of energy like biodiesel, ethanol, charcoal or directly for heat and electricity. The plants and animals that decay and produce this bioenergy consume water for sustenance [36].

2.3 Water demand for electricity production

2.3.1 Non-Renewable sources
The idea of the "water-electricity nexus" was created as a result of the fact that water is required for the majority of thermoelectric power generation processes [37, 38, 39], and it is the most utilized material for condensing steam leaving turbines at thermoelectric power installations and cooling thermoelectric power generator [38,41-42]. Based on data from the U.S Geological Survey of 2018 more than 80% of the USA electricity comes from thermoelectric power plants, as do 67% of the world's total net electricity production, which places a heavy need on water resources. Nearly 40% of the freshwater that was harvested in the United States was utilized to produce thermoelectric electricity in 2010 [40].

The use and dependence on natural gas for electric power sources has been on the increase over the years in the USA. It made up to 30% of the total electric power source in 2012 [43], and has increased to over 40% as of 2022 making it the largest source of electricity with up to 4120 terawatt hours (TWh) [44]. This increase is the result of more economical shale and tight gas extraction brought on by advances in horizontal drilling and hydraulic fracturing. From a life cycle approach, transitioning to natural gas combined cycle (NGCC) electric generation units (EGUs) from coal-fired power production units would result in considerable water savings [45]. According to the [46] report the U.S. electric power sector’s thermal water consumption decreased by 10.5% from 53.1 trillion gallons in 2019 to 47.5 trillion gallons in 2020 continuing the downward trend due to an increase in the use of renewable energy and NGCC.

14% of the world’s electricity is produced through nuclear power [47]. Nuclear power is the third-largest source of energy production in the United States, contributing around 20% of all electricity produced. Based on data from the World Nuclear Association (WNA), US nuclear power reactors generated 809.41 terawatt-hours of electricity in total in 2019. As the world's largest nuclear power producer, the US is responsible for nearly 30% of all nuclear electricity generation worldwide. Depending on the cooling methods, nuclear plants consume between 20-60 gallons of water for every kWh of electricity they produce. Therefore, it is challenging to use nuclear power technology in areas with a lack of water [48].

2.3.2 Renewable sources

Hydroelectricity remains the largest renewable source of electricity as 2022 data from the International Energy Agency stated that generation increased by almost 70TWh, reaching a total of 4300 TWh. Although it needs a lot of water, hydroelectric power is a significant energy source that can help to satisfy the world's rising energy needs, contributing to 21% of the world's electricity use and 86% of its use for renewable energy [47]. Hydropower plants have a range of adverse environmental consequences, including ecosystem impacts, water quality degradation, and consumptive water loss [48]. A significant amount of water is lost by evaporation from the open water surface as a result of water storage in a reservoir. However, determining the consumptive water demand for hydroelectricity equipment is challenging due to numerous dams and reservoirs, climate variation, regional variability, and various operational modes [49, 50]. According to [51] average water losses by evaporation varied from 12 × 109 in 1995 to 15.53 × 109 m3 in 2007 with an average of 13.62 × 109 m3 /year.

In other forms of renewable energy like wind energy and photovoltaic cells dependence on water for generation is nearly negligible[52]. From Global Wind Energy Council forecast anticipates that by 2030, wind energy will make up 20% of global electricity generation thereby reducing the withdrawal of water for generation. [53] in their work on the reduction of cooling water consumption due to photovoltaic and wind electricity feed also projected that by 2050 there would be a 7% reduction in annual water consumption across Germany due to their renewable energy goals.

2.4 Energy demand for water systems

According to estimates, the removal and disposal of water for urban residents and industries consumes 2-3% of all worldwide energy [54]. Due to unforeseen policy consequences and increased pressure to use and maintain the quality of water resources, the energy used by the water industry is enormous and is projected to keep increasing [55]. Water and wastewater treatment uses processes that require a lot of energy [30] according to research, long-distance water transport and desalination are major energy consumers per unit volume [56].

[57] divides energy demand for water supply, use, and disposal chain into five stages, including source and conveyance, treatment, distribution, end use, and wastewater treatment. Additionally, [58] established a methodical approach to examining energy from different water sources (surface water and groundwater pumping), methods of treatment (treatment of high-ambient quality raw water and brackish or seawater), intended end-use, distribution methods, and amounts of water loss in the system through leakage and evaporation, as well as levels of wastewater treatment. [59] further added energy use for water recycling and reclamation.

Existing research on water-energy nexus examines several topics in several fields. [60] measured US water-related energy use to create a standard for the nation's energy-water intense sector. [61] estimated the water-related energy consumption for eight countries including the USA, Spain, Japan, China, Australia, Brazil, Singapore, and the Netherlands, and compared them with the global average of 4%, with Spain having the most water-related electricity consumption with 6.2% and California with 5.2%. [62] examined India’s water treatment systems’ life cycle energy use.

3. Water-Carbon Nexus (WCN)

The term "water-carbon nexus" is used to describe carbon emissions that are connected to water. Recent WCN studies like [30] are into three categories. The first category focuses on carbon emissions from water systems that are caused by energy use [63, 64, 65] and the use of water and carbon emissions in energy systems [66, 67] which are both the most important aspect of water-carbon nexus. The second category examines carbon emissions brought on by the production of hydroelectricity [68], and the last category focuses on the connections between energy and the interplay between water and carbon in urban economic systems [69]. This research appears to have some issues. First, the study area is frequently restricted to the water or energy sectors; second, the research area is frequently restricted to the boundaries of the urban geographic or economic system; and third, the research subject is typically restricted to carbon emissions associated with the energy sector. But in addition to the energy-related carbon emissions linked to water systems, diffuse and fugitive emissions should also be taken into account, examples include diffuse methane emissions, nitrous oxide emissions from sewers and facilities that dispose of waste, or methane released from flooded vegetation in water reservoirs. Also, deforestation, urbanization, and agriculture all required for the expansion of cities are examples of human activities that can change the landscape and have an impact on the carbon and water cycles. A case example is the felling of trees which results in more runoff and less carbon sequestration.

For the development of sustainable cities, concentrating on all water-related carbon emissions in a water system may be more important. [70] in their study of the synergy between water resources in response to climate change stated the modification of precipitation patterns, causes more severe droughts or floods and affects the development and distribution of vegetation, climate change can upset the relationship between water and carbon. Temperature variations may also affect the amount of carbon released from soil and glaciers. Sustainable solutions to the WCN by several researchers like [71, 72] would be finding sustainable answers that handle carbon and water management in harmony. To maximize both water supplies and carbon sequestration, this may entail reforestation, wetland restoration, and better land-use planning.

4. Energy-Carbon Nexus

Climate change is the first environmental factor, and it is accelerating due to greenhouse gases produced by human activities. Burning fossil fuels, like coal, to produce power is one of the main contributors to climate change [73]. Around 40% of the world's energy-related carbon dioxide (CO2) emissions are linked to emissions from the generation of electricity and heat [74]. The sector's strong reliance on fossil fuels is the cause of its high emission proportion. Coal is the main fossil fuel used to produce about two-thirds of the world's power [75]. [76] in their study of the carbon footprint of Xiamen City in China developed a hybrid method that combines the use of process analysis and an economic input-output life cycle assessment It uses process analysis and an economic input-output life cycle assessment (EIO-LCA) model to assess the carbon footprint of Xiamen City in China in light of these three criteria. The results indicate that about 96% of the total carbon emissions are attributable to energy use.

The city level is the primary frontier for energy savings and emissions reductions in the industrial sector concerning the industry agglomeration region. Energy used in the industrial sector in 2010 totaled 2.311 billion tons of coal equivalent, or 69.5% of China's overall energy consumption CITATION Men19 \l 1033 [30] Additionally, 77% of China's overall CO2 emissions were caused by the industrial sector.

Iron and cement are two important building materials for newly constructed structures and infrastructure for urban development. CITATION Mor14 \l 1033 \m Has13[77, 78] researched the iron steel and cement industries and discovered that advances in technology can result in significant reductions in energy consumption intensity. The research of various industry development scenarios reveals that the two main actions that can lead to energy savings are the promotion of technology and alterations to industrial structure. China's cement iron and steel industries will mostly rely on structural changes and technology promotion to reduce emissions, respectively.

5. Prospects for future research on the water-energy-carbon nexus

Currently, the majority of nexus studies of complex urban systems concentrate on dependency assessments of two elements, such as energy related to water, water-related to energy, water-related to carbon, and carbon connected to both energy and water. These studies do analyze that separate resource consumption, environmental emissions, and economic growth. It is challenging to analyze the interactions and trade-offs between energy, water, and carbon emissions when only two factors are considered. These three components are interrelated in many ways. The energy-water-carbon nexus has received scant attention in previous research; therefore, it is vital to examine this relationship by looking at the three systems as a whole.

6. Conclusion

The intricate interplay of water, energy, and carbon emphasizes the importance of a comprehensive approach to environmental sustainability and protection. This manuscript emphasizes the interconnection of these critical elements and also highlights the importance of integrated methods and policies to address their nexus.

Recognizing the deep impact of water usage on energy generation and the consequential carbon emissions, it is evident that any intervention in one element profoundly impacts the others. To mitigate the negative effects of this nexus requires multifaceted solutions that consider efficiency, conservation, and renewable alternatives across different areas.

This paper emphasizes the importance of adopting sustainable behaviors, technology Innovations, and robust policy frameworks. Collaboration among various stakeholders, which should include governments, industries, researchers, and even the communities, is paramount in navigating this nexus toward a more sustainable future.

As we walk through the complexities of the water-energy-carbon nexus, it is crucial to take a proactive approach, leveraging technological advancements, encouraging changes in behavior that promote sustainability, and supporting a circular economy approach. By doing these, we can pave a path for environmental sustainability, assuring the preservation of resources for future generations.

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