CHEMICAL ENGINEERING TRANSACTIONS
VOL. 83, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183025

Methods and Trends for Water-Energy-Carbon Emissions Nexus Assessment

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The Water-Energy-Carbon Emissions (WEC) nexus has been drawing increasing attention. However, very few studies, to date, were conducted to comprehensively review the assessment approaches, challenges and trends of future works for regional and sectoral CWC nexus. This paper aims to analyse and review the WEC nexus assessment methods, challenges of WEC network management and ways to go in the future. Eight different kinds of WEC nexus assessment methods are introduced, as well as their advantages and drawback. Five future work directions of WEC nexus assessment are proposed. This study provides a better understanding of the WEC nexus and more approaches to assess the WEC nexus.

1. Introduction

A massive amount of production and different kinds of services are shared between different regions and sectors worldwide. Water utilisation, energy consumption and carbon emissions have been increasingly studied and profoundly entwined from both regional and global perspectives. As three significant environmental strategy elements, water, energy and carbon are together studied by increasing authors as the Water-Energy-Carbon Emissions (WEC) nexus (Wang et al., 2020a). A better understanding of the WEC nexus is pivotal for decreasing the environmental footprints, mitigating the climate change, contributing to sustainable development (Li et al., 2020). It is crucial to explore the linkage between water utilisation, energy consumption and carbon emissions. As shown in Figure 1 (Ifaei and Yoo, 2019), water, energy, and carbon sectors are separately represented by a blue ellipse, a red rectangle, and a grey pentagon. The coloured arrows indicate the interactions (such as energy consumption during water withdrawal) among these three sectors. Three main kinds of linkage of different sectors are illustrated: internal effect (arrows begin and end in a sector), net forward linkages (arrows begin in a sector) and net backward linkages (arrows end in a sector).

Water, energy and carbon network are highly focused on in different studies under different topics. Wang et al. (2020c) explored the sectoral WEC nexus of China by employing the environmental input-output approach. The embodied water and energy consumption and embodied carbon emissions were analysed; the sectoral coefficients of water utilisation, energy consumption and CO_2 emissions were identified. They found that several sectors are water-, energy- and carbon-emission-intensive, including heavy industry, light industry, and service industry. Chen et al. (2019) analysed the WEC nexus from the inter-regional scale perspective. They explored the embodied and direct WEC nexus, demonstrated that the WEC nexus footprint intensities were much higher than the total footprint intensities. Li et al. (2020) reviewed the WECN, including the concepts, research focuses, mechanisms, and methodologies. Because of its extremely significant for regional sustainability and the environment healthy, the WECN has been arousing increasing attention worldwide. The WECN mechanism for the power generation sector, water service sector, agriculture production sector, and the household sector have also been concluded by Li et al. (2020). It has been shown that water, energy and carbon emissions are among the most significant elements for maintaining environment sustainability (Wang et al., 2020d).

Integrated approaches, for example, input-output (IO) model, LCA method, etc., should be comprehensively considered for analysing the broader system, in terms of WEC nexus in the future. The WEC nexus assessment can also be extended from the social system, economic system to the ecosystem (Wang et al., 2020b). Understanding the mechanism of the interactions between vegetation dynamics and the water cycle is pivotal

Paper Received: 19/10/2020; Revised: 07/11/2020; Accepted: 15/11/2020
Please cite this article as: Wang X.-C., Klemeš J.J., Varbanov P.S., 2021, Methods and Trends for Water-Energy-Carbon Emissions Nexus Assessment, Chemical Engineering Transactions, 83, 145-150 DOI:10.3303/CET2183025

for determining regional and global water and carbon budgets (Zeng et al., 2020). They modelled the WECN of the ecosystem by integrating the hydrological model and a biogeochemical model, which provided an effective model for the simulation of water-carbon cycles. Nair et al. (2014) reviewed the WECN of urban water systems, comprehensively surveyed various studies conducted in various regions of the world and focusing on individual or multiple subsystems of an urban water system.
The most article focused on the WEC nexus of different sectors at different scales. However, very few studies, to date, were designed to comprehensively review the analysis approaches and impact factors of regional and sectoral CWC nexus. For narrowing the research gap, this paper aims to review the WEC nexus assessment methods and relevant impact factors.

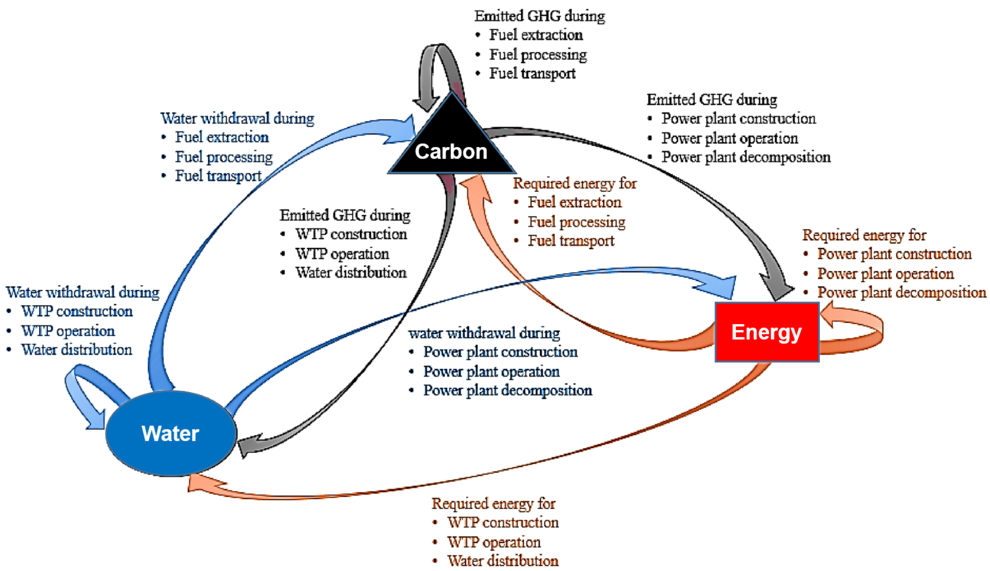

Figure 1: Schematic diagram of WEC nexus, developed from (Ifaei and Yoo, 2019). WTP: water treatment plants.

2. Approaches for analysing WEC Nexus

Both regional and global WEC networks are complicated systems. They usually involve multiple sectors and regions, especially under the globalisation. The interregional and international trades are proofed highly depended by all countries worldwide, especially under the COVID-19 pandemic (Klemeš et al., 2020).
The approaches that can be employed to assess the WEC nexus with multi-region and –sector should have the following characteristics:
(i) Focus on multiple sectors from the supply chain perspective;
(ii) Accurately identify the linkages among different regions;
(iii) Identify the virtual material flows between different sectors and regions, including embodied water flows, embodied energy flows and embodied carbon flows;
(iv) Comprehensively assess the environmental impacts of different human activities, including carbon emissions, etc.;
(v) Accurately quantify the efficiencies of different materials, including water utilisation coefficients, energy consumption coefficients, and carbon emissions coefficients.

Several methods can be used for exploring the critical flows in the CWE network, like Material Flow Analysis - MFA (Sun et al., 2017), Life Cycle Assessment - LCA (Friedrich et al., 2020). These methods are flexible for wider usage and are easier for obtaining data, as well as being convenient to quantify environmental performance. Another widely used method is input-output analysis, which is good for analysing the embodied impacts under the situation of the multiregional and multi-sectoral flow system. Both quality and quantity of data are the most significant challenges for these tools, like MFA (Islam and Huda, 2019). Multi-Criteria analysis could be another useful tool for solving similar issues (Antanasijević et al., 2017); however, it is not with the same quantitative level as MRIO. Although the MRIO highly depends on big sets of systematic and consistent data, which are usually slightly lagging, it is a widely used and effective method with good robustness for handling economic and environmental data from the supply chain perspective (Wang et al., 2020a). More methods and their advantages and drawbacks are analysed in Table 1.

Table 1: Methods for assessing the WEC nexus, as well as their advantages, limitations and case studies.

Methods	Advantages	Drawbacks	Case Studies
Input-output analysis (IO)	The full supply chain is taken into consideration, involving multi-sectors; Exploring the complex network and system with multi-region; Truncation errors are avoided.	Highly depends on big sets of systematic and consistent data; Aggregation error due to combining different products under a single sector; City-level IO database is limited.	WEC nexus of the EU27 (Wang et al., 2020a)
Life cycle assessment (LCA)	Assessing from the supply chain perspective; Data are easy to obtain; Several different LCA databases are available; Regional and global scale; Provided environmental impacts.	Not suitable to explore the WEC flows characteristics; Difficult to identify the specific linkages among different regions.	Environmental impacts of the water-energy system (Grubert and Stokes-Draut, 2020)
Fuzzy clustering approach	Introducing the concept of “partial truth”; Provide environmental impacts Provide efficient resource allocation.	Uncertainties in partitioning; Comparatively subjective optimisation definition	Building WEC management (Alghamdi et al., 2020)
Material flow analysis (MFA)	Data requirement is comparatively easier; The computational procedure is comparatively easier	Supply chain assessment is partial; Cannot identify the influence for a multi-sectors and -regions system.	Industrial process water-energy nexus (Amón et al., 2018).
System dynamics modelling	A comprehensive model with comparative completed function; Especially good for the closed-loop network; The cause and effect relationships can be provided.	Losing details might happen during the simplification of the complex systems; Difficult to identify the specific linkages among different regions.	Urban Food-Water-Energy system analysis (Hu et al., 2019).
Ecological network analysis (ENA)	Suitable for complex and multi-region product system; Can identify the control and dependency relationship.	Aggregation error; Comparatively complex model.	WEC nexus under energy system (Wang et al., 2019).
Optimisation and mathematical modelling	Usually focuses on analysing the driving factors; Allows analysis of specific process with the key variables having major impacts in the system.	Mathematical complexities; Subjective optimisation definition; Not good at identifying the influence for a multi-sectors and -regions system.	Agricultural water-energy-food nexus management (Li et al., 2019).
Emergy analysis	By translating all-natural and economic flows and stocks to solar energy unit comprehensively examine the sustainability of the studied system.	Computational complexities and data-intensive; Not good at identifying the influence for a multi-sectors and -regions system.	Oil and gas sector WEC nexus (Huang et al., 2019)

3. Challenges of WEC system management

Global greenhouse gas (GHG) emissions have been continually raising despite the implementation of the United Nation Sustainable Development Goals (SDGs) and the Framework Convention on Climate Change (UNFCCC) (Roe et al., 2019). The world is running well behind its already insufficient targets of limiting global warming to below 2 ℃ above pre-industrial levels and pursuing efforts to limit it to 1.5 degrees (Climate Action Tracker, 2020), as shown in Figure 2.

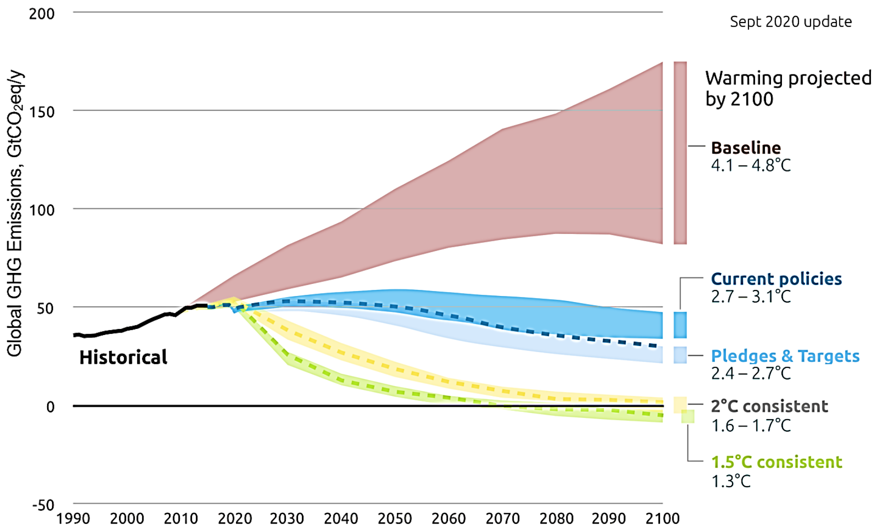

Figure 2: 2100 Warming Projections – Emissions and expected warming based on pledges and current policies, developed from (Climate Action Tracker, 2020)

All measures and targets usually designed around these GHG emissions; however, this is not the complete picture. The SDGs, where water and clean energy within the context of a sustainable partnership are spelt-out so that a sustainable future is built for humankind equitably and in peace. Climate change, water scarcity and energy risk would bring significant uncertainty in regional and global sustainable strategies. The impact factors of the WEC system are widely and complicated influenced by different kinds of drivers, including regional and global policies and strategies, etc. The only way to achieve the goal is to improve efficiency and to adjust the energy structures, increasing the renewable energy share.
Another challenge is that the goals for water management or water utilisation strategies are vague, which is unlike the goals about carbon and energy. For example, the main objective of EU water policies is to ensure water quality standards (European Commission, 2020). There are relevant strategies and actions to mitigate water scarcity, to improve the sustainability of the water systems and to increase water savings and efficiencies, such as launching the Blueprint to Safeguard Europe’s Water Resources. However, there are large gaps in water policies. For example, the water aspect is overlooked for the EU27 in terms of Germany, France and Italy with limited water for their industrial activities (Blue-Cloud, 2020). More polluting activities might be transferred to upstream countries or elsewhere, as they need massive embodied water to support their industrial development.

4. Ways to go

The current works, to date, provide a promising outlook for WEC nexus in terms of different aspects. They contribute to the evaluating of trade-offs, improvement of regional sustainability, a decrease of the environmental impact, optimisation of WEC nexus strategies, etc. However, different limitations still exist. As contributed by Zhang et al. (2018), future study of which focused on the Food-Water-Energy nexus should focus on the following questions: where is the system boundary; how to solve the problem of data and modelling uncertainty; how to define the mechanism of nexus and how to evaluate the coupled nexus systems. It could be a good reference for the trends of WEC nexus studies, however, not enough. As far as the authors understanding, for the future trends of WEC nexus, five aspects should be taken into consideration:

(i) Proper system boundary definition, including both micro and macro directions. It is of great significance to identify and define the study system boundary of WEC nexus. Different system boundaries might result in different assessment results. Especially for some specific method, like LCA, different boundaries are with different environmental impacts results. An appropriate boundary is important to guarantee the accuracy of results. A narrow boundary might leave out some important interlinkages, resulting to under-estimate the integrity and complexity of WEC nexus system. By contrast, larger system boundaries are usually with more complicated processes, data preparation and model development.

(ii) Proper assessments methods development. As analysed in section 2, there are different kinds of methods can be used for assessing the WEC nexus. However, each of them has different drawbacks when assessing WEC nexus. To date, there is no recognised method that proper for WEC system modelling, especially aims at the complicated system boundaries.
(iii) Consistent and completed data preparation. WEC nexus is a complicated system involving multiple regions, sectors, materials, policies, etc. Great amounts of different kinds of data are symbiotic with the system, including economic data, environmental data (water utilisation, energy consumption, carbon emissions, etc.), policy requirements, etc. However, these data are currently processing and handling by different departments, which are usually less connected. The data systematism is not well organised. The consistent and completed data are pressing.
(iv) More in-depth WEC nexus mechanism identification. The mechanism of the WEC system is very complicated. There is no study, to date, can clearly explain the mechanism of the whole system, except some can provide partial explanations (Wang et al., 2020c).
(v) Global and systemic considerations of WEC nexus. Most studies focused on the WEC nexus of individual or multiple sectors, city or regions level. The global and systemic studies of WEC nexus still need more in-depth analysis.

5. Conclusions

This paper provides a review of assessment methods, challenges and trends of future works in terms of WEC nexus analysis. The key findings are summarised below:

a) Eight different kinds of WEC nexus assessment methods have been introduced, including input-output analysis, life cycle assessment, fuzzy clustering approach, material flow analysis, system dynamics modelling, ecological network analysis, optimisation and mathematical modelling and emergy analysis. The advantages, drawbacks and case studies are analysed as well.
b) The challenges of WEC nexus management have been discussed. They include: the daunting challenge of climate change remains; energy efficiency and structure need improvement; water management or water utilisation strategies are vague. It is crucial to make comprehensive regional and global WEC system management strategies.
c) Five future work directions of WEC nexus assessment are proposed, including proper system boundary definition, from both micro and macro directions; proper assessments methods development; consistent and completed data preparation; more in-depth WEC nexus mechanism identification; global and systemic considerations of WEC nexus.

The complicated linkages among sectors or regions in WEC nexus still need to be systematically researched. Previously, fossil fuel security was king in the global energy landscape, but climate changes, increasing human population growth combined with the effects of the global COVID-19 pandemic are causing unprecedented societal changes. Globally, total water and energy consumption continue to rise. Energy consumption will continue to increase as well, although with more variability. This study provides a better understanding of the WEC nexus and more approaches to assess the WEX nexus, as well as the trends for future studies.

Acknowledgements

This research has been supported by the project “Sustainable Process Integration Laboratory – SPIL”, project No. CZ.02.1.01/0.0/0.0/15_003/0000456 funded by EU “CZ Operational Programme Research, Development and Education”.

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