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EVALUACIÓN DE LA EFICIENCIA DEL NEXO AGUA-ENERGÍA MEDIANTE INDICADORES EXERGÉTICOS

TESIS PRESENTADA PARA EL GRADO ACADÉMICO DE DOCTOR EN ENERGÍAS

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Dedicatoria

Este trabajo va dedicado a los que realmente saben amar y reconocen que la fragilidad humana se convierte en resistencia

Santiago, Tito, Rosita, mi familia y la profe Yannay

A ellos les digo, extiéndanse para alcanzar lo aleatorio y donde nadie ha llegado,

Extiéndase en espiral….

Extiéndase en espiral….

También, a aquellas personas que desde el anonimato y en silencio con sus lagrimas contribuyen en la cosecha de los frutos de la ciencia.

Mis agradecimientos a la Universidad de Concepción y al proyecto Fondecyt 11170302: Accounting of land use as natural resources by integrating thermodynamics with ecology principles por su financiación y la oportunidad de acceder a nuevo conocimiento.

Abstract

In the following thesis, the efficiency of the water-energy nexus (WEN) is evaluated in two study cases using exergetic indicators. This study work has been structured in three chapters: in the first one, a bibliographic review on WEN is carried out, focusing on the main problems or gaps in its evaluation; The second chapter addresses the evaluation of the nexus among different strategic resources, in particular, water, energy and land, using as study case: the Chilean Electric System (CES) and the Drinking Water Treatment System (DWT) in Chile. For both cases, the methodological potentialities of the Life Cycle Analysis (LCA) were combined with the exergetic analysis, obtaining metrics that allowed to quantify the impact of the WEN. Finally, in the third chapter, the main strengths, weaknesses and challenges of the usage of exergy as a metric for the evaluation of efficiency within the context of the nexus are exposed.

From the bibliographic review, it is concluded that the water-energy nexus (WEN) has been quantified using numerous tools, methods and methodologies in various contexts and scales; which has made it difficult to replicate and compare study cases at different scales and/or geographic locations. Simultaneously, it is observed that the efficiency of the usage of resources throughout its supply chain has not been considered, limiting the studies to the physical quantification of each resource in the nexus. That is why this thesis proposes exergy as a tool for evaluating WEN, since it allows, par excellence, to quantify the efficiency of different resources throughout supply chains. In the case study of the Chilean Electric System (CES), the efficiency of the water-energy-land nexus (WELN) was evaluated through the exergy indicators Cumulative Exergy Consumption (CExC) and the Cumulative Degree of Perfection (CDP). The results showed that the production of 1 MWh of electricity required 17.3 GJex, with the energy component of the nexus (fossil and renewable energy sources) being the main contributor (99%). Renewable energy technologies represented the highest CDP indices (13%-46%) within the nexus associated with lower CExC and higher technological efficiencies in relation to non-renewable energies (14% -19%).

On the other hand, for the Drinking Water Treatment (DWT) system, the CExC values showed significant differences between the regions (1-50 MJex/m^3), depending on the quality of the raw water sources, the energy consumption indicators in the transport of the fluid (pumping) and the technology used for the treatment of drinking water. The highest CExC were recorded in the northern areas (30-50 MJex/m^3) compared to the central-south regions (1-10 MJex/m^3) due to the poor quality of the water in the first; therefore, more energy-intensive technologies (reverse osmosis) were required for its purification.

In general, the evaluation of the nexus for both study cases showed that water resources and land use manifest an almost negligible contribution to the CExC, due to the low quality of these resources compared to the energy component. However, this does not mean that they are irrelevant for the sustainability of the electricity system and water treatment at a regional and local scale.

To validate the above, the Water Stress Index (WSI) and the Blue Water Footprint (BWF) were applied to the DWT study case. Both were differentiated by regions, to highlight the fundamental role of water resources within the WEN. In this sense, both indicators showed a strong geographic dependence due to climatic variability, where the WSI gradually increased from the extreme south to the northern areas, registering the highest water stress index (0.5-1) for the north center zones. The highest values of WSI and CExC demonstrated that the water-energy nexus becomes stronger for the northern zone of Chile than the rest of the regions, which could progressively intensify towards the central zone due to the higher BWF (26-50 m^3/s) and the effect of climate change.

Based on the results obtained in the second chapter, the contribution of exergy is highlighted as a promising tool in the evaluation of the nexus among resources, by allowing the unification of metrics and the evaluation of the efficiency in the use of resources. However, one of the limitations found was that it does not visualize the relevance of water and land resources within the nexus. Therefore, it is recommended to complement it with other tools associated with sustainability, such as, environmental footprints (hydro and ecological ones) and resource scarcity indices, among others. Although exergy is a unifying metric, the results obtained may not be easy to understand for decision-makers due to the multidimensional characteristics of the nexus; therefore, it is recommended to complement the analysis with other tools, such as Multi-Criteria Decision Analysis (MCDA).

Resumen

En la presente tesis se evaluó la eficiencia del nexo agua-energía (WEN) en dos casos de estudio, utilizando indicadores exergéticos. Este trabajo se ha estructurado en tres capítulos: en el *primer capítulo*, se realizó una revisión bibliográfica sobre el WEN focalizando los principales problemas o vacíos en su evaluación; en el *segundo capítulo* se abordó la evaluación del nexo entre diferentes recursos estratégicos, en particular agua, energía y suelo utilizando como casos de estudio: el Sistema Eléctrico Nacional (CES) y el de Tratamiento de Agua Potable (DWT) en Chile. Para ambos casos, se combinaron las potencialidades metodológicas del Análisis de Ciclo Vida (LCA) con el análisis exergético y se obtuvieron métricas que permitieron cuantificar el impacto del WEN. Finalmente, en el *tercer capítulo*, se exponen las principales fortalezas, debilidades y desafíos del uso de la exergía como métrica para la evaluación de la eficiencia dentro del contexto del nexo.

A partir de la revisión bibliográfica se concluye que el nexo agua-energía (WEN) ha sido cuantificado usando numerosas herramientas, métodos y metodologías en diversos contextos y escalas; lo que ha dificultado su replicabilidad y comparación entre casos de estudio a diferentes escalas y/o ubicaciones geográficas. Al mismo tiempo, se observa que la eficiencia del uso de los recursos a lo largo de toda su cadena de suministro no se ha considerado, por lo que los estudios se limitan a la cuantificación física de cada recurso en el nexo. Por consiguiente, esta tesis se propone la exergía como herramienta para la evaluación del WEN, dado que ésta permite, por excelencia, cuantificar la eficiencia de distintos recursos a lo largo de las cadenas de suministro.

En el caso de estudio del Sistema Eléctrico Nacional (CES), se evaluó la eficiencia del nexo agua-energía-suelo (WELN) a través de los indicadores exergéticos Consumo Acumulado de Exergía (CExC) y el Grado Acumulado de Perfección (CDP). Los resultados mostraron que la producción de 1 MWh de electricidad requirió 17.3 GJex, siendo el componente energético del nexo (fuentes de energía fósiles y renovables) el principal contribuyente (99%). Las tecnologías de energía renovable representaron los mayores índices CDP (13%-46%) dentro del nexo, asociado a un menor CExC, así como mayores eficiencias tecnológicas en relación con las energías no renovables (14%-19%).

Por otro lado, para el sistema de Tratamiento de Agua Potable (DWT), los valores de CExC mostraron diferencias significativas entre las regiones (1–50 MJex/m^3), dependiendo de la calidad de las fuentes de agua cruda, los indicadores de consumo energético en el transporte del fluido (bombeo) y la tecnología usada para el tratamiento de agua potable. Los mayores CExC se registraron en las zonas norte (30-50 MJex/m^3) en comparación con las regiones centro-sur (1-10 MJex/m^3) debido a la mala calidad del agua en las primeras; por lo que se requirieron tecnologías más intensivas en energía (ósmosis inversa) para su potabilización.

En general la evaluación del nexo para ambos casos de estudio demostró que los recursos agua y uso del suelo muestran una contribución en el CExC casi despreciable, debido a la baja calidad de dichos recursos en comparación con el componente energético. Sin embargo, esto no significa que sean irrelevantes para la sustentabilidad del sistema eléctrico y potabilización, tanto a escala regional como local.

Para validar lo anterior, se aplicaron al caso de estudio DWT, el Índice de Estrés Hídrico (WSI) y la Huella Hídrica Azul (BWF) diferenciados por regiones, para resaltar el papel fundamental de los recursos hídricos dentro del nexo agua-energía. En este sentido, ambos indicadores mostraron una fuerte dependencia geográfica debido a la variabilidad climática, donde el WSI se incrementó gradualmente desde el extremo sur hasta las zonas norte, registrando el índice de estrés hídrico más alto (0,5-1) para las zonas centro norte. Los valores más altos de WSI y CExC demostraron que el nexo agua-energía se hace más fuerte para la zona norte de Chile que para el resto de las regiones, lo que podría intensificarse progresivamente hacia la zona central debido a los mayores BWF (26-50 m^3/s) y al efecto del cambio climático.

A partir de los resultados obtenidos en el *segundo capítulo*, se destaca la contribución de la exergía como una herramienta prometedora en la evaluación del nexo entre recursos, al permitir la unificación de métricas y la evaluación de la eficiencia en el uso de los recursos. Sin embargo, se ha encontrado una limitación: no visualiza la relevancia de los recursos hídricos y terrestres dentro del nexo. Por lo tanto, se recomienda complementarlo con otras herramientas asociadas a la sustentabilidad como las huellas ambientales (hídrica, ecológica) y los índices de escasez de recursos, entre otros. A pesar que la exergía es una métrica unificadora, puede que los resultados obtenidos no sean de fácil comprensión para los tomadores de decisiones debido a las características multidimensionales del nexo; por ende, se recomienda complementar el análisis con otras herramientas, como es el caso del Análisis de Decisiones Multi-Mriterio (MCDA).

Índice

Lista de acrónimos

BWF	Blue Water Footprint
BWM	Best Wast Method
CDP	Cumulative Degree Perfection
CES	Chilean Electric System
CExC	Cumulative Exergy Consumption
CF	Carbon Footprint
CGE	Computable General Equilibrium
CODAS	Combinative Distance Based Assessment
DWT	Drinking Water Treatment
EEA	Extended Exergy Accounting
EF	Ecological Footprint
ELCA	Exergetic Life Cycle Assessment
EPANET	Enviromental Protection Agency (modeling software)
FAO	Food and Agriculture Organization of the United Nations
HOMER	Hybrid Optimization Model for Multiple Energy Resources
IOA	Input - Output Analysis
LA	Linkage Analysis
LCA	Life Cycle Analysis
LEAP	Long - range Energy Alternative and Planning
LEN	Land - Energy Nexus
MCDA	Multiple - Criteria Decision Analysis
MRIO	Multi - Regional Input - output
MuSIASEM	MultiScale Integrated Analysis of Societal and Ecosystem Metabolism
NPP	Net Primary Production
OECD	Organisation for Economic Co-operation and Development
PA	Process Analysis
SAM	System Advisor Model
TEC	Termo-Ecological Cost
UNECE	United Nations Economic Commision for Europe
WEAP	Water Evaluation And Planning System
WEN	Water - Energy Nexus
WELN	Water - Energy-Land Nexus
WLN	Water - Land Nexus
WSI	Water Scarcity Index

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Introducción

El rápido crecimiento de la población mundial, la urbanización y las actividades antropogénicas han contribuido al aumento de la demanda y presión sobre los recursos naturales, especialmente sobre el agua, la energía y el suelo (Guan et al., 2019). En este contexto surge el nexo, un enfoque holístico e integral que busca la gestión conjunta de los recursos para lograr su uso eficiente y sustentable (Hoff, 2011). La Organización de las Naciones Unidas en la Conferencia de Bonn (2011, 2019) señaló que la disponibilidad del agua y la energía representa uno de los desafíos más importantes que enfrentan los territorios en la actualidad (Ahmad et al., 2020). Estos antecedentes así como la cada vez más importante- preocupación por la seguridad hídrica y energética futura, el nexo ha recibido un interés creciente en el ámbito académico y de los tomadores de decisiones (Ding et al., 2020; Lele et al., 2013; Pahl-Wostl, 2017).

Las interdependencias o nexos se cuantifican normalmente a través de cantidades físicas asociadas a la demanda del recurso (agua, energía, suelo, etc.), indistintamente del contexto de evaluación. El nexo agua-energía (WEN), es uno de los más estudiados y ha sido evaluado cualitativa y cuantitativamente en una amplia variedad de sistemas, utilizando numerosas métricas, herramientas, métodos y/o metodologías. Ante la amplia variedad de trabajos que incorporan múltiples herramientas, sistemas y contextos, el nexo se puede clasificar según su escala de aplicación en micro (procesos), meso (sectores productivos) y macro escalas (regiones, cuenca, país) (Dai et al., 2018) .

La **micro-escala** o escala de procesos, puede dividirse en dos líneas de trabajo: las líneas (i) *agua para energía* y (ii) *energía para agua*. En esta escala, distintos investigadores han evaluado el nexo mediante la estimación de la demanda de agua dulce y/o energía en procesos asociados a ambas líneas. Dentro de los procesos más estudiados en la línea *agua para energía* se encuentra el suministro de energía (extracción, procesamiento y distribución de energía) (Basheer and Elagib, 2019; Larsen and Drews, 2019; Mielke et al., 2010; Tan and Zhi, 2016), mientras por el lado de *energía para agua* resaltan los sistemas urbanos de tratamiento de agua (potabilización, distribución y tratamiento de aguas servidas) (Sharif et al., 2019; Xiang and Jia, 2019; Bukhary et al., 2020; Wakeel et al., 2016). La evaluación cuantitativa del nexo a escala de procesos se ha basado en indicadores de intensidad hídrica (Mielke et al., 2010; Xiang and Jia, 2019), energética (Bukhary et al., 2019; Molinos-Senante and Sala-Garrido, 2017; Plappally and Lienhard, 2012; Wakeel et al., 2016), huellas ambientales (Gu et al., 2016; Spang et al., 2014) y el Análisis de Ciclo de Vida (Muñoz et al., 2010; Stokes and Horvath, 2006; Raluy et al., 2005).

Como se indicará previamente, el WEN también ha sido estudiado en sectores productivos y áreas geográficas, que constituyen las escalas **meso y macro** del nexo, respectivamente. En estas escalas, el nexo ha sido evaluado y analizado en sectores claves para la economía. Entre estos destacan los sectores energético, sanitario e industrial tanto a nivel de país, como de ciudad y cuenca hidrográfica (Li et al., 2019; Lu and Chen, 2016; Moredia et al., 2017; Nair et al., 2014; Peña, 2018; Tidwell et al., 2012; Tidwell and Pebbles, 2015). Inicialmente, los trabajos asociados a estas escalas fueron diagnósticos fundados en macro-indicadores sobre la distribución del agua y la energía en los sectores económicos y áreas geográficas mencionadas. Particularmente, para los diagnósticos a macro-escala se desarrollaron métodos y metodologías integradas que buscaron generar una visualización simple de los indicadores de intensidad y del uso de los recursos mediante cartografías, diagramas de flujo o plataformas virtuales (Giampietro et al. 2013, 2014; Strasser et al. 2016). En la actualidad, los estudios para ambas escalas poseen diferentes propósitos, como optimizar el uso del agua y la energía en la cadena de suministro de un producto, usando como base modelos matemáticos multivariables *bottom-up* o métodos híbridos de las huellas ambientales y LCA (Ahmad et al., 2020; Fan et al., 2019; Guan et al., 2019; Sambito and Freni, 2021; Shirkey et al., 2021). Otras aplicaciones están orientadas a realizar proyecciones futuras mediante modelos multi-variables sobre la disponibilidad de ambos recursos para un sector en específico o todos los sectores productivos, con la finalidad de desarrollar estrategias y políticas hacia el uso sustentable de los recursos hídricos y energéticos locales (Ji et al., 2020; Lin et al., 2019; Liu et al., 2021; Sun et al., 2021).

Si bien, existe una variedad de herramientas, métodos y metodologías para la evaluación del nexo agua-energía en las diferentes escalas, todas exhiben limitaciones, por lo que persiste la falta de consenso sobre cuál es el enfoque metodológico más apropiado. En la micro-escala, la mayoría de los trabajos se especializan en un tipo de recurso o entrada (agua directa y/o indirecta, energía directa y/o indirecta) de un proceso o etapa de la cadena de producción, ya sea del suministro energético o del tratamiento de agua. En la meso y macro-escala, aunque se han evaluado ambos tipos de recursos y entradas en diferentes sectores productivos, la combinación y desarrollo de herramientas para cada contexto ha provocado la existencia de una amplia variedad de métricas, lo que limita las experiencias comparativas, la replicabilidad de resultados y la evaluación de la eficiencia en el uso de los recursos hídricos y energéticos (Dai et al., 2018; Endo et al., 2020). En este sentido, las herramientas basadas en el concepto de exergía pueden constituir un aporte en la evaluación del nexo entre recursos, ya que permite su evaluación o cuantificación sistémica utilizando una métrica común (MJ de exergía) o unificada. Por otro lado, el enfoque de exergía acumulada ofrece una visión clara de la degradación del capital natural involucrado a través de toda la cadena de producción de cualquier sistema productivo.

En efecto, la exergía representa específicamente la máxima cantidad de trabajo útil que puede realizar un sistema, flujo de materia y energía respecto a su estado de referencia (Dincer and Rosen, 2007; Kotas, 1997; Wall, 1977). En términos de la sostenibilidad, esta expresa la estrecha relación entre los sistemas y el entorno. Las herramientas exergéticas son reconocidas por su sólida base conceptual, su capacidad de unificar diferentes medidas y, además, de cuantificar el uso sostenible de los recursos naturales, mediante la eficiencia. El análisis de exergía ha sido ampliamente utilizado en la optimización de los recursos en procesos manufactureros (Bayrak et al., 2017; Giacalone et al., 2018; Marais et al., 2017), sectores productivos (Rodríguez-Merchán et al., 2019; Zhang et al., 2017) e incluso en áreas geográficas (Dai et al., 2014; B. Zhang et al., 2018). También, se han desarrollado otras herramientas de evaluación que integran principios ecológicos, ambientales y económicos, como el análisis exergo-ambiental (Boyano et al., 2011; Hamut et al., 2013), económico (Bonforte et al., 2017; Tsatsaronis, 2007), contabilidad de la exergía extendida (Aghbashlo et al., 2018) y exergo-ecología (Calvo et al., 2016).

Por otra parte, los procesos de producción de agua potable y energía constituyen uno de los pilares del desarrollo económico de cualquier región o país. Por tal motivo y ante la evidente interconexión entre estos sistemas, muchos estudios se han preocupado por evaluar el nexo entre ellos.

Es importante destacar, que el WEN tiene una dependencia multifactorial y presenta dinámicas influenciadas por características locales. Este carácter multidimensional hace que la intensidad del nexo agua-energía cambie en función de la variabilidad climática, la disponibilidad y calidad del agua, las diferencias en los usos y la demanda del agua y energía, las características socio-económicas, los avances tecnológicos (eficiencia hídrica y energética) y las políticas relacionadas a la gestión de ambos recursos.

A la fecha, son escasos los trabajos en el contexto de Chile que abordan el nexo con todas sus dimensiones. Los pocos trabajos realizados para Chile subrayan la provisión de agua y energía (sector energético y sanitario) como aspectos críticos del nexo debido a las condiciones climáticas, económicas y políticas locales (Kelly and Negroni, 2020; Ponce-Oliva et al., 2021; Vergara et al., 2017). Sin embargo, todavía no existen estudios que hagan un seguimiento exhaustivo del uso del agua y la energía por la cadena de suministro de la electricidad y el agua potable a nivel nacional. Tampoco existen evidencias del uso de la exergía como herramienta para evaluar su eficiencia.

En concordancia con lo anterior, el objetivo principal de este estudio es evaluar el nexo agua-energía (WEN) y su eficiencia mediante herramientas exergéticas, usando como casos de estudio los sistemas de generación de energía y producción de agua potable a diferentes escalas. Esta tesis constituye la primera contribución en la cuantificación de la eficiencia en el uso de los recursos dentro del nexo a lo largo de toda su cadena de suministro usando la exergía como métrica de evaluación. Realizar un seguimiento a ambos recursos en dichas cadenas puede facilitar la detección de las ineficiencias y, por consiguiente, la posibilidad de diseñar medidas de optimización más efectivas; lo que es, al mismo tiempo, la base de una gestión proactiva y eficiente entre los recursos dentro del territorio, garantizando la seguridad en su suministro.

I. Hipótesis

Es posible cuantificar la eficiencia del uso directo e indirecto de los recursos agua y energía en los sistemas de producción de energía eléctrica y tratamiento de agua potable, mediante la evaluación exergética del nexo entre ellos.

II. Objetivo general

Evaluar la eficiencia del nexo agua-energía en sistemas de producción de energía eléctrica y de agua potable, usando indicadores exergéticos.

III. Objetivos específicos

1. Desarrollar un análisis crítico sobre los distintos enfoques metodológicos utilizados en la evaluación del nexo entre el agua y la energía de los sistemas de abastecimiento energético y tratamiento de agua potable.
2. Evaluar exergéticamente el nexo agua-energía en los sistemas de producción de energía eléctrica y de agua potable.
3. Analizar las fortalezas, debilidades y desafíos en la evaluación exergética del nexo.

Capítulo 1

Conceptos fundamentales

1.1 Orígenes y definición del nexo

Históricamente, la demanda de agua, energía, suelo y otros recursos naturales ha sido impulsada por el crecimiento de la población, la urbanización y el desarrollo económico. Se estima que para el 2050 la demanda hídrica y energética aumentará un 50%, en comparación con los niveles reportados en el 2015 (IRENA, 2015). Esta situación supone una creciente presión, no solo sobre el agua y la energía, sino sobre los sistemas naturales (suelo y ecosistemas) proveedores de estos recursos, lo que pone de relieve la estrecha interrelación o nexo que existe entre ellos (Zhang, et al., 2018). Hasta ahora, la gestión tradicional de los recursos se ha hecho de forma aislada, desconociendo que, por diversos factores, la demanda de un recurso afecta directa e indirectamente a otros recursos y sectores. Ilustremos lo aquí planteado con un ejemplo: tanto el cultivo de alimentos como la producción de energía requieren de agua, suelo y energía, asimismo, requieren de estos la producción y el tratamiento de agua, las actividades industriales y la expansión urbana. De esta manera se genera una competencia por los recursos. En consecuencia, comprender y abordar estas interacciones de manera sistémica es vital para lograr una gestión eficiente (Keairns et al., 2016).

En el contexto descrito surge el enfoque *"nexo"*, que busca integrar la gestión de recursos naturales considerados estratégicos para lograr su gestión eficiente y sustentable. El nexo fue explorado en metodologías desarrolladas por Giampietro et al. (2013, 2014) y Strasser et al. (2016) en colaboración con la FAO y la UNECE, respectivamente. Estas metodologías se especializaron en el reconocimiento y evaluación de las interdependencias entre recursos vitales para el desarrollo, como los ya mencionados (Olsson, 2013).

En el nexo, las interdependencias se definen como las dependencias de los sectores y procesos productivos a los recursos naturales, donde la falta de disponibilidad de alguno puede afectar negativamente el provisionamiento de los otros. Lo anterior, muestra la importancia de una gestión consensuada que contribuya con el buen estado de los recursos en un territorio (Keairns et al., 2016). Finalmente, este enfoque proporciona información relevante que facilita a los tomadores de decisiones poder diseñar políticas e instrumentos de gestión coherentes, que promuevan sinergias entre los sectores, lo que minimiza los *trade offs* (Hoff, 2011).

1.2 Tipos de nexos

Actualmente, se han desarrollado tres tipos de nexo según se muestra en la figura 1: el nexo agua-energía, el nexo agua-energía-suelo y el nexo agua-energía-suelo-ecosistema.

a) **Nexo agua-energía (WEN):** estudia y evalúa las dependencias de las cadenas de suministro de energía (combustibles y electricidad) y del tratamiento de agua (potabilización, distribución y tratamiento) a los recursos hídricos y energéticos (Hamiche et al., 2016). En los últimos años, el WEN ha sido evaluado en sistemas con diferentes alcances, desde la escala de procesos hasta la escala geográfica (Dai et al., 2018; Endo et al., 2020). Debido a la variedad de intereses y objetivos alrededor del nexo agua-energía son múltiples los métodos y herramientas desarrollados, en su mayoría desde la asignación de recursos, es decir: la demanda. Sin embargo, aún hay brechas en su cuantificación que no han encontrado una solución adecuada, como por ejemplo la transición entre escalas y el contabilizar los recursos con un método único. Si bien, el nexo cuantitativamente aún le falta consolidarse, variedad de autores y tomadores de decisiones lo consideran un enfoque útil en la buena gestión de los recursos naturales en un territorio (Ding et al., 2020; Endo et al., 2020; Scott et al., 2011). Por todo lo expuesto, es posible concluir que es el nexo más avanzado en términos cuantitativos.

b) **Nexo agua-energía-suelo (WELN):** contabiliza las dependencias de cualquier proceso, sector productivo y/o área geográfica a los recursos hídricos, energéticos y usos del suelo. Cabe mencionar que el suelo no fue considerado un recurso estratégico en el ámbito científico, menos para los gobiernos, hasta la propuesta metodológica desarrollada por Giampietro et al. (2013, 2014), donde se indicó que la tierra es un recurso limitado y sujeto a la presión de variedad de actividades antrópicas. En estudios actuales, el suelo ha sido contabilizado en el WELN principalmente con indicadores en procesos y sectores productivos en los que resulta necesario, como en la producción de biocombustibles, la agricultura, la ganadería y el suministro eléctrico (generación fotovoltaica). En contraposición, puede decirse que todavía son pocos los trabajos que han explorado nuevas herramientas para evaluar explícitamente el suelo desde el nexo, así como los efectos y la eficiencia de su uso.

c) **Nexo agua-energía-suelo-ecosistema (WELEN):** se caracteriza por reconocer a los ecosistemas como el recurso central del nexo, ya que entiende que su estado incide en la disponibilidad de los demás recursos naturales. Por lo anterior, los temas relacionados con la gestión de los ecosistemas requirió pronta atención, de allí que Strasser et al. (2016, 2020) desarrollara una metodología cualitativa dirigida a las cuencas transfronterizas. Aunque esta no significó un gran avance en el aspecto cuantitativo del nexo, resaltó la disputa entre países por los recursos hídricos y cómo la productividad de los servicios ecosistémicos se ve afectada por fenómenos ambientales como el cambio climático. A la fecha, este nexo ha sido estudiado de manera extendida en sectores y procesos altamente susceptibles a estos fenómenos, tales como el sector energético (generación hidroeléctrica), agrícola (cultivo de alimentos) y sanitario. A diferencia de los nexos descritos en los párrafos anteriores, es posible afirmar que los trabajos sobre el WELEN priorizan las estrategias de cooperación, voluntad política y planificación para contribuir en la mitigación de los efectos del cambio climático en la disponibilidad de recursos como el agua.

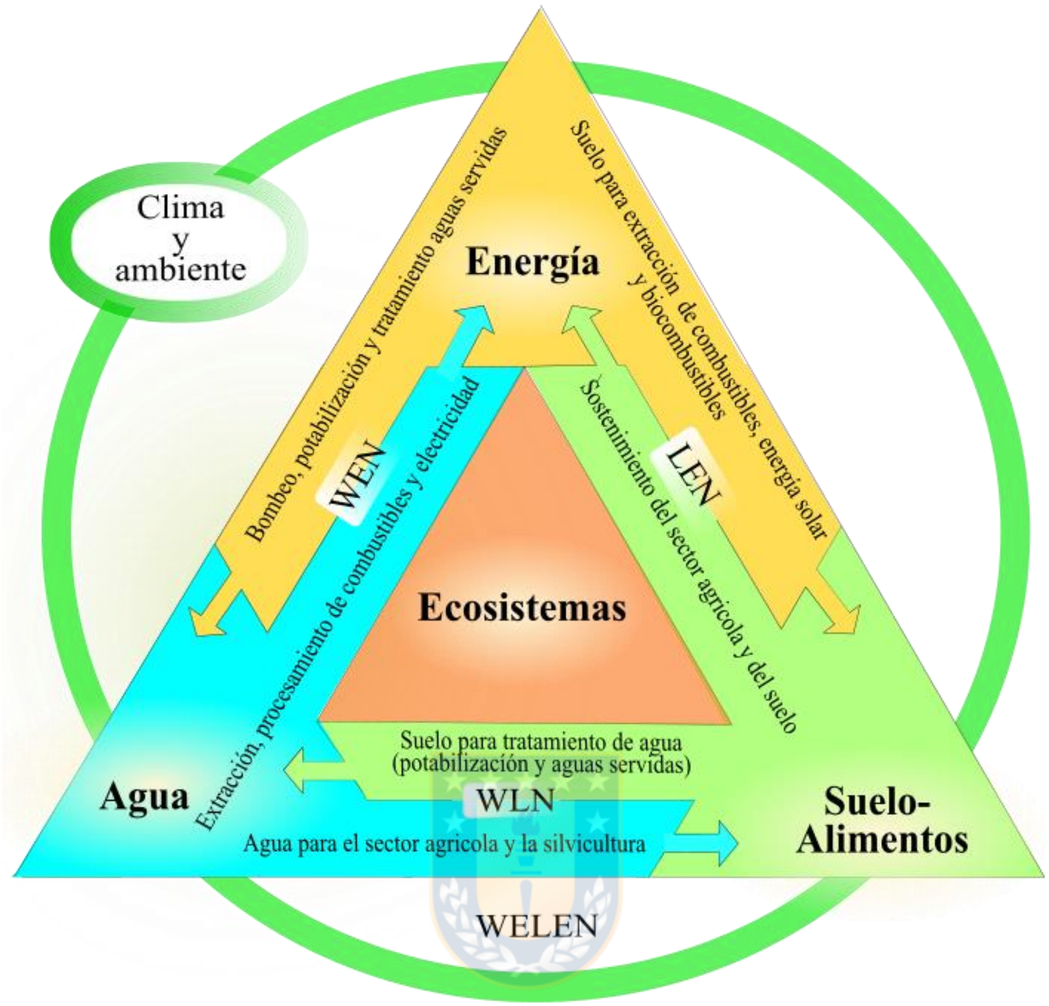

Figura 1. Algunos ejemplos de las interacciones entre el agua-energía-alimentos-ecosistema (WELEN) que constituyen los diferentes tipos de nexos. (Fuente: elaboración propia)

Este trabajo hará énfasis en el nexo agua-energía (WEN) debido al papel estratégico de estos recursos en el desarrollo económico (Griggs et al., 2013) y la alta vulnerabilidad en su suministro futuro por el cambio climático (Scott et al., 2011; Ding et al., 2020; Lele et al., 2013; Pahl-Wostl, 2017).

Estudios realizados sobre el WEN han destacado que la cadena de suministro del agua requiere de la disponibilidad y buena gestión de la energía (y viceversa), independientemente de la variedad de objetivos, alcances y contextos considerados. Desde esta perspectiva, se ha demostrado el rol fundamental que desempeñan los recursos hídricos en la extracción de combustibles fósiles (Hardy et al., 2012; Chang et al., 2016) y en la generación de electricidad con procesos térmicos (Chang et al., 2016). En la producción de agua se ha puesto en evidencia la forma en que el tipo de tecnología de potabilización o de tratamiento de aguas residuales incide en la demanda energética (Santana et al., 2014). Para estos recursos, también se han efectuado estudios que buscan determinar los impactos ambientales asociados a su uso, considerando el tipo de fuente y las tecnologías de conversión (Pradeleix et al., 2014). Aunque esta variedad de trabajos ha contribuido a la comprensión del nexo agua-energía, la definición de interdependencia requiere ser modificada, puesto que su evaluación gira alrededor de los procesos, no de los recursos. En consecuencia, para poder evaluar las interdependencias, además de las entradas directas de agua y energía, se debe considerar el agua y la energía indirecta implicada en su extracción, generación y tratamiento. Lo anterior permitiría hacer un seguimiento de los recursos por su cadena de valor, lo que ofrece un panorama general sobre su uso y, además, facilita la distinción de aquellas etapas energo-intensivas o altamente dependientes del agua.

La mayoría de los estudios mencionados anteriormente se han focalizado en la evaluación de la demanda directa e indirecta de agua que se consume en la cadena de suministro de energía, así como de la energía del sistema productor y suministrador de agua para diferentes usos y sectores (Hamiche et al., 2016). Esta evaluación se realiza mediante distintas herramientas, aspecto que será discutido en detalle más adelante.

Es necesario destacar que el suelo también constituye un recurso vital que está sometido a constante presión, ya sea por el crecimiento poblacional como por la competencia por su uso (Guzmán et al., 2019). Respecto a este punto, ocurre de manera creciente entre la producción de biocombustibles y alimentos, tanto por el uso del suelo como por el uso del agua, motivado por el desarrollo de la bioenergía. Sumado a esto, se genera una nueva presión sobre los ecosistemas y la biodiversidad (Zhang et al., 2018). Lo precedente ha llevado a extender el denominado nexo agua-energía a nexo agua-energía-alimentos (Giampietro et al., 2013, 2014) y nexo agua-energía-alimentos-ecosistemas (Strasser et al., 2016). Al incorporar los alimentos y los ecosistemas a la red de interrelaciones, estos enfoques han permitido enriquecer la mirada holística que sustenta el nexo. Sin embargo, pocos trabajos han incorporado el uso del suelo de manera explícita; solo aparece implícitamente en evaluaciones nexo agua-energía-alimentos. Su incorporación al enfoque tradicional del nexo agua-energía obedece al carácter limitado de este recurso, el que se presenta como un recurso estratégico para la agricultura y la producción de bioenergía (Silalertruksa and Gheewala, 2019, 2018).

1.3 Escalas de evaluación del nexo

El nexo entre recursos agua, energía, suelo y ecosistema, ha sido evaluado en distintos niveles: procesos, sectores productivos y áreas geográficas, como se muestra en la figura 2. Estos niveles constituyen las escalas de evaluación en las que puede clasificarse el nexo: la (i) macro-escala que abarca áreas geográficas tales como ciudades, regiones, países y cuencas transfronterizas, la (ii) meso-escala que incluye los sectores productivos y la (iii) micro-escala que considera los procesos productivos.

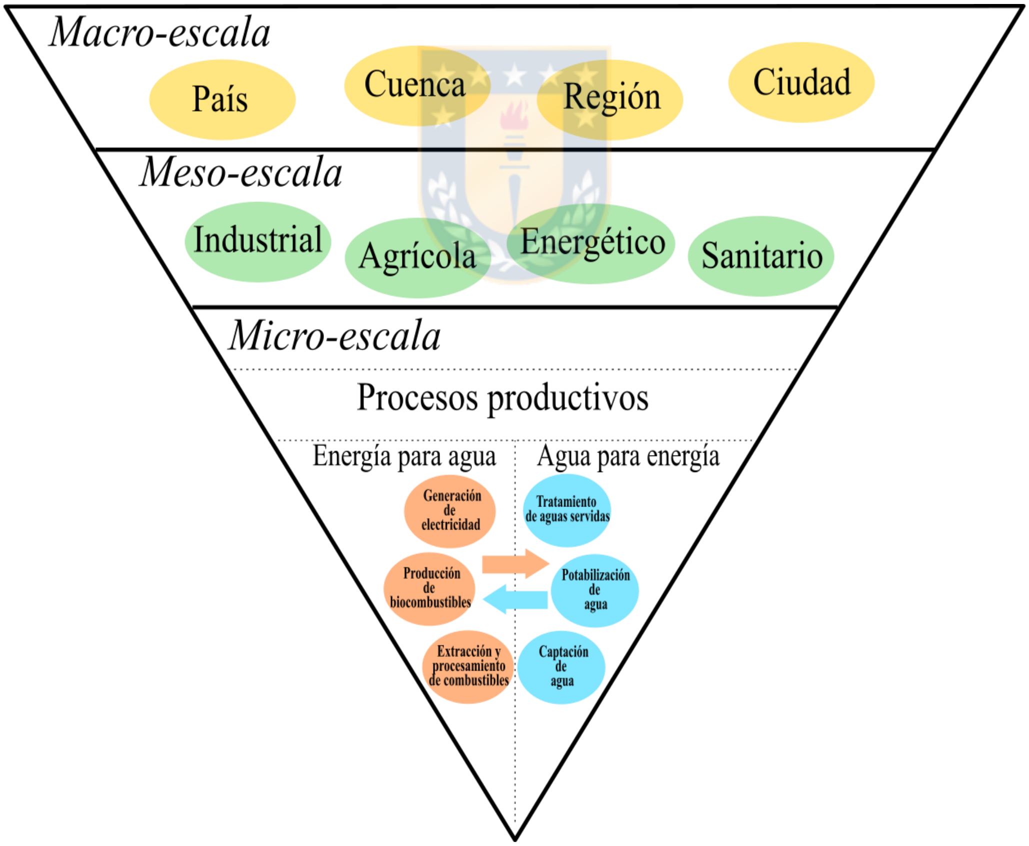

Figura 2. Escalas de evaluación del nexo entre los recursos agua-energía. (Fuente: elaboración propia)

En la **micro-escala**, haciendo énfasis en el nexo agua-energía (WEN), se distinguen dos líneas de trabajo: i) agua para energía y ii) energía para agua. Estas líneas se han focalizado principalmente en contabilizar la demanda (directa e indirecta) de agua y/o energía en la cadena de suministro de ambos recursos, así como en la optimización de su uso. En la línea agua para energía se han evaluado procesos de extracción (Hamiche et al., 2016; Mielke et al., 2010; Tan and Zhi, 2016), procesamiento de combustibles (Gould, 2016; Mielke et al., 2010; Pacetti et al., 2015; Spang et al., 2014) y generación electrica mediante recursos renovables y no-renovables (Campos-Lopes et al., 2020; Feng et al., 2014; Scanlon et al., 2013; You et al., 2021). Por otro lado, en la línea energía para agua se han estudiado exhaustivamente el bombeo de agua (Luna et al., 2019; Martin-Candilejo and Santill, 2020; Page et al., 2017; Plappally and Lienhard, 2012), potabilización (incluyendo desalinización) (Bukhary et al., 2019; Garfí et al., 2016; Vakilifard et al., 2018), distribución (Bolognesi et al., 2014; Sharif et al., 2019; Xiang and Jia, 2019) y tratamiento de aguas servidas (Gu et al., 2016; Nowak, 2003; Zappone et al., 2014). Independientemente de la línea de trabajo, los autores concluyen que los parámetros de relevancia en la demanda y optimización de ambos recursos corresponden a variables técnicas, como la eficiencia de las tecnologías involucradas en los sistemas, además de factores externos, como la topografía y las normas de calidad establecidas para los procesos de potabilización y tratamiento de aguas residuales.

A nivel de **meso-escala** han sido ampliamente abordados sectores claves para la economía, entre ellos el energético, el industrial, el agrícola y el sanitario. Los primeros trabajos tenían como propósito evaluar indicadores de intensidad del uso del agua y de la energía basados en estadísticas sectoriales, no desde información de los procesos que los integran (Okadera et al., 2014; Sanders and Webber, 2011; Walker et al., 2013; Wang et al., 2012). En años recientes, los estudios han buscado superar esta brecha desarrollando métodos multi-variables o híbridos *top-down* que han contribuido con la optimización de estos recursos, logrando hacer proyecciones sobre la disponibilidad de ambos recursos bajo distintos escenarios. Los resultados señalan que el sector industrial, sanitario, energético y agrícola son los focos del consumo directo e indirecto de agua y energía, al ser los principales vehículos en la formación de capital de los territorios (Guan et al., 2019; Wang et al., 2019). Particularmente, en el sector energético la perspectiva *top-down* cuestionó la viabilidad de las energías renovables, ya que la fabricación de las tecnologías asociadas a estas exhiben una alta demanda de recursos naturales (Cai et al., 2014; Liao et al., 2019; Wu and Chen, 2017). En el sector sanitario, los trabajos coincidieron en que las transferencias de agua a largas distancias y el estado de las redes de distribución tienen una contribución significativa en la demanda energética, debido a la baja eficiencia de las bombas y las constantes fugas (Sambito and Freni, 2021; Sarbu, 2016). Por lo tanto, los trabajos de optimización se enfocaron en mejoras operacionales, como el mantenimiento o cambio de la infraestructura. Para la producción de bioenergía (Abdali et al., 2021; You et al., 2021), productos agrícolas (Armengot et al., 2021; Karamian et al., 2021) e industriales (Abbas et al., 2020; Hashemi et al., 2021) se han diseñado redes óptimas de suministro según criterios tecnológicos, climáticos y ecológicos, acompañados de recomendaciones desde la gobernanza. Por otro lado, las proyecciones sobre la disponibilidad de los recursos hídricos y energéticos demuestran la vulnerabilidad de estos sectores productivos al cambio climático, donde se proyecta una disminución significativa de los regímenes hidrológicos (Arriagada et al., 2019; Basheer and Elagib, 2019; Gaudard et al., 2017), pero un incremento en la demanda de ambos recursos entre el 40–77% para el 2030 (Cai et al., 2014; Wang et al., 2019). Incluso, en escenarios donde se integran medidas económicas y políticas, como la implementacion de impuestos ambientales o una gestion sostenible, los autores concuerdan en que el riesgo de escasez de ambos recursos aún está presente (Larsen and Drews, 2019; Lv et al., 2018; Nazari et al., 2015; Sun et al., 2021).

A **macro-escala** se han desarrollado trabajos cualitativos y cuantitativos principalmente a nivel país, ciudad y de cuenca hidrográfica. A diferencia de las escalas antes descritas, el principal aporte de los estudios en áreas geográficas corresponde a la generación de información sobre el estado del agua y la energía en un territorio, priorizando al mismo tiempo la formulación de estrategias de gobernanza para su uso sostenible. Al principio, estos estudios eran de carácter cualitativo o semi-cuantitativo, basados en métodos o metodologías constituidas por indicadores multivariables que ofrecían una mirada general del nexo en un territorio o cuenca hidrográfica (Giampietro et al., 2013, 2014; Strasser et al., 2016 ; Scott et al., 2011). Sin embargo, últimamente los trabajos a macro-escala se han focalizado en la eficiencia en el uso del agua y la energía en las cadenas de suministro, empleando métodos con mayor especificidad y/o complejidad. Los casos de estudio más recurrentes se encuentran en China (Duan and Chen, 2020; Fan et al., 2018; Feng et al., 2019; Guan et al., 2019; Li et al., 2019; Lv et al., 2021) y con menos frecuencia en otros países, como Estados Unidos (Khalkhali et al., 2018; Tarroja et al., 2014) y México (Moredia et al., 2017), donde los resultados evidenciaron cómo la baja eficiencia de las unidades base (tecnologías disponibles) y de las estructuras físicas de suministro energético y sanitarias pueden incrementar entre un 50–70% la demanda total de agua y energía a nivel nacional y ciudad, de acuerdo a las proyecciones de los autores. En estudios transnacionales se encontró que algunos países europeos pertenecientes a la OECD y asiáticos tienen una eficiencia promedio del 45% en el uso de los recursos. Cabe mencionar que la eficiencia se definió en función de los recursos implicados en la provisión de un bien o servicio, dejando de lado el concepto de eficiencia tecnológica. Además, exaltaron los beneficios de una gestión conjunta, de la distribución equitativa y de la jerarquización de los recursos locales (Basheer et al., 2018; Chenoweth and Al-Masri, 2021; Ibrahim et al., 2019; Strasser and Stec, 2020).

A partir de lo planteado anteriormente, se puede sostener que uno de los objetivos de los estudios actuales corresponde a la evaluación del nexo entre el agua y la energía en la meso y macro-escala desde la escala de procesos, ya que el seguimiento de ambos recursos por las cadenas de suministro puede facilitar la detección de las ineficiencias y diseñar medidas de optimización más efectivas. Por otra parte, los sectores productivos situados en un territorio se abastecen de agua y energía, siendo recursos inevitables en procesos unitarios, ya sea de la industria química, textil, agrícola, etc. Por lo tanto, los procesos que proveen de agua, electricidad y combustibles pueden considerarse como las unidades base en el desarrollo económico de cualquier país. En consecuencia, dichos procesos deberían ser la base fundamental en la evaluación del nexo en las escalas superiores, optando por un enfoque *bottom-up*. Los estudios de caso asociados al presente trabajo se centran en los procesos base y en la eficiencia del nexo en su cadena de suministro.

1.4 Herramientas de evaluación del nexo agua-energía (WEN)

A partir del análisis realizado sobre la literatura, se obtiene que la selección de las herramientas de evaluación del nexo está íntimamente relacionada con la escala de evaluación del mismo, aspecto que ya ha sido discutido. Consecuentemente, verificamos la existencia de múltiples herramientas de evaluación, lo que dificulta el poder comparar los resultados obtenidos entre diferentes estudios (Dai et al., 2018).

A micro-escala se han utilizado herramientas que permiten estimar demandas directas e indirectas de agua y energía; algunas de las más utilizadas han sido los indicadores de consumo especifico (Larsen and Drews, 2019; Mielke et al., 2010; Scanlon et al., 2013; Spang et al., 2014; Tan and Zhi, 2016; Xiang and Jia, 2019; Zappone et al., 2014), LCA (Pradeleix et al., 2014; Sharif et al., 2019) y plataformas virtuales como SAM (Bukhary et al., 2019; Campos-Lopes et al., 2020). Para fines de optimización, se desarrollaron modelos numéricos como HOMER (Brandoni and Bosnjakovic, 2017; Martin-Candilejo and Santill, 2020; You et al., 2021), versiones híbridas o combinaciones entre el LCA, IOA y las huellas ambientales (Feng et al., 2014; Gu et al., 2016; Pacetti et al., 2015), además de programas digitales de dominio publico como EPANET (Bolognesi et al., 2014; Luna et al., 2019).

A meso-escala han predominado indicadores y métodos que buscan mejorar la eficiencia o desempeño ambiental de distintos sectores productivos, entre ellos la CF en combinación con PA y LCA (Armengot et al., 2021; Sambito and Freni, 2021; Shirkey et al., 2021; Wang et al., 2012), BWF (Liao et al., 2019; Okadera et al., 2014), IOA híbridos (Lu and Chen, 2016; Wang et al., 2017), modelos matemáticos multivariables (Abbas et al., 2020; Hashemi et al., 2021; Karamian et al., 2021; You et al., 2021) y otros, como los métodos CODAS-BWM (Abdali et al., 2021). En los últimos años, el interés por la disponibilidad del agua y la energía a mediano y largo plazo llevó a los autores a proponer nuevos IOA (Okadera et al., 2015; Mo et al., 2014) o modelos matemáticos compuestos por análisis hidrológicos, energéticos y de transferencia de recursos que consideran variables climáticas, posibles cambios políticos, económicos y las dinámicas de consumo futuras, como el LEAP y WEAP (Liu et al., 2021; Fan et al., 2019; Fan et al., 2018; Gu tan el., 2014; Ji et al., 2020; Lee et al., 2018; Lin et al., 2019). Es importante señalar que las simulaciones usualmente recurren a representaciones visuales, como los grafos o diagramas de flujo.

A macro-escala se han desarrollado distintos marcos metodológicos basados en indicadores o modelos sociales, económicos y ambientales que ofrecen un panorama general sobre los recursos en un territorio limitado o cuenca, indicando su disponibilidad o intensidad en su uso (Giamprieto et al., 2013, 2014; Strasser et al., 2016; Chenoweth and Al-Masri, 2021; Guan et al., 2019; Yang et al., 2016; Duan and Chen, 2020; Strasser and Stec, 2020). Cada una de estas herramientas, como el CGE (Fan et al., 2018; Sun et al., 2021) o MRIO-LA (Fang and Chen, 2018, 2017a, 2017b; Feng et al., 2019), han sido diseñadas para responder a objetivos específicos de su contexto. Sin embargo, destacaron las metodologías desarrolladas por Giamprieto et al., (2013, 2014) y Strasser et al., (2016), al ser precursores de la evaluación del nexo a macro-escala. La primera desarrolló un soporte computacional denominado MuSIASEM para tener una perspectiva del nexo y la segunda una hoja de ruta semi-cuantitativa para una gestión transfronteriza.

Las herramientas mencionadas en los párrafos anteriores son resumidas y clasificadas en la figura 3. Estas son categorizadas por escala (micro, meso y macro-escala) y por objetivo, es decir, si buscan cuantificar el nexo, optimizarlo, proyectar escenarios o desarrollar medidas de gobernanza.

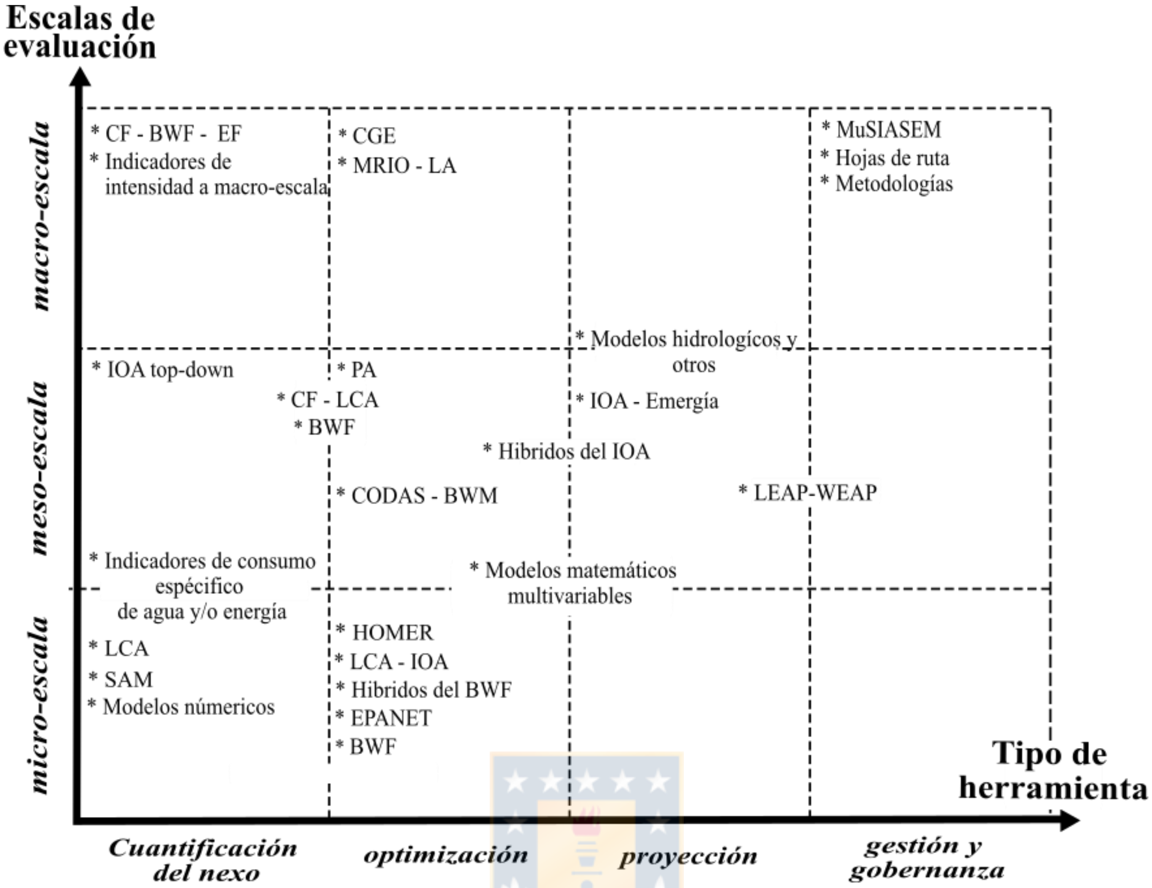

Figura 3. Herramientas de evaluación del nexo agua-energía. (Fuente: elaboración propia)

Considerando lo discutido anteriormente, las herramientas usadas para la evaluación del nexo solamente permiten analizar y comparar de forma independiente el agua y la energía implicada en los procesos y sectores productivos. Las diferentes métricas usadas no permiten evaluar de forma integrada los recursos mediante una misma unidad, lo que dificulta el análisis y la comparación de resultados. Además, no aportan información sobre la calidad en su uso, siendo el factor eficiencia una variable importante en la gestión sostenible. Como aspecto concluyente, puede decirse que **la evaluación del nexo carece de una adecuada métrica que permita cuantificar la eficiencia del uso del agua y la energía, y otros recursos, como el suelo.** En este sentido, las herramientas basadas en el concepto de exergía pueden ser un aporte relevante en la evaluación de la calidad del uso de los recursos, además de visualizarlos de forma holística y expresarlos en una misma unidad (MJ de exergía).

La exergía representa la máxima cantidad de trabajo útil que puede realizar un sistema, flujo de materia y energía respecto a su estado de referencia (Wall, 1977; Kotas, 1997; Ibrahim

Dincer, 2007). De esta forma, cuantifica las ineficiencias de cualquier proceso, ofreciendo la oportunidad de evaluar el impacto ambiental y la sostenibilidad en función de los recursos (Bilgen and Sarikaya, 2015). Además, la exergía permite contabilizar todos los flujos materiales, energéticos y el suelo en una misma métrica, tal como se ha indicado, en términos de MJ de exergía (MJex).

Por otra parte, el concepto de exergía ha sido la base del desarrollo de diferentes herramientas de evaluación que integran principios ecológicos, ambientales y económicos, lo que convierte a la exergía en un concepto importante en el desarrollo sostenible, como se muestra en la figura 4 (Bilgen and Sarıkaya, 2015; Romero and Linares, 2014). Entre los principales métodos fundamentados en el concepto de exergía se encuentran el ELCA (Ozbilen et al., 2012), exergo economía (Bonforte et al., 2017; Tsatsaronis, 2007), exergo ambiental (Boyano et al., 2011; Hamut et al., 2013), contabilidad de la exergía extendida (Aghbashlo et al., 2018) y exergo ecología (Calvo et al., 2016).

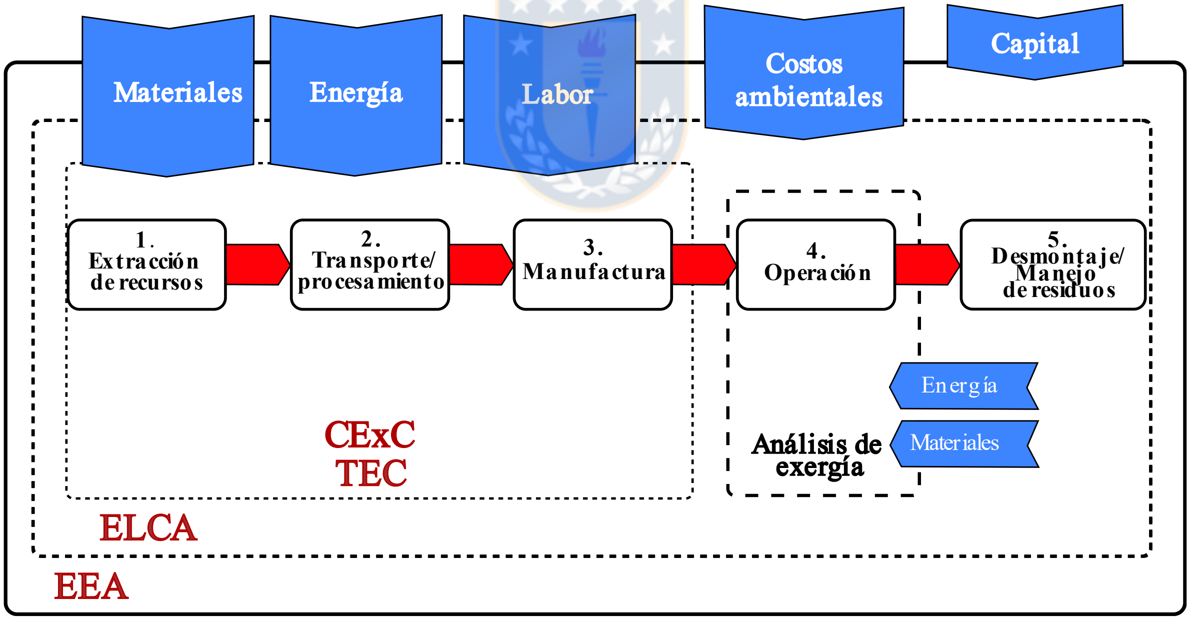

Figura 4. Herramientas basadas en el análisis exergético. (Fuente: Rocco et al., (2014))

A nivel de procesos o micro-escala el análisis de exergía ha sido ampliamente utilizado para la optimización de procesos industriales, específicamente en la contribución de mejorar la eficiencia en procesos térmicos (Bayrak et a., 2017; Marais et al., 2017; Ibrahim et al., 2018) y químicos (Antonova et al., 2015; Giacalone et al., 2018). Este análisis les ha permitido a los autores localizar dónde ocurren las mayores pérdidas y también establecer lineamientos para optimizar el funcionamiento de los equipos. Los análisis exergéticos también se han implementado a meso-escala, abordando sectores tales como: el energético (Zhang et al., 2018), el industrial (Selicati et al., 2020 ; Bühler et al., 2016), agrícola (Ahamed et al., 2011; Chen et al., 2009) y el residencial (Zhang et al., 2018). A macro-escala podría decirse que se encuentran los estudios conocidos como exergía aplicados a la sociedad, en los que se contabiliza la exergía de todos los recursos implicados en los sectores productivos situados en un territorio. Este tipo de estudio se ha efectuado en países como China (Zhang et al., 2018; Zhang et al., 2012; Chen et al., 2014) y Turquía (Seckin et al., 2012).

Cabe considerar que la exergía también ha mostrado importantes aportes en la contabilización de otros recursos estratégicos como el suelo. En ese sentido, Alvarenga et al., (2013a) y Taelman et al. (2016) han desarrollado factores de caracterización expresados en MJex/m^2 año para determinar el impacto de las intervenciones humanas sobre el uso del suelo, integrando los principios ecológicos (NPP) y el concepto de exergía. Estos estudios podrían contribuir significativamente a visualizar de mejor manera el suelo como recurso en el contexto del nexo, aspecto que actualmente constituye un desafío, según se ha argumentado anteriormente.

En función de lo discutido, la exergía emerge como una herramienta relevante de evaluación en los estudios de sostenibilidad, debido a su sólido basamento termodinámico y, a su vez, a la estrecha relación de los procesos con el medio ambiente, siendo este último el que sustenta los sistemas productivos existentes en un territorio; aspecto que, por lo general, no ha sido considerado en los enfoques clásicos de sustentabilidad. Además, permite unificar métricas entre recursos (materiales, energéticos y uso de suelo), lo que posibilita darle seguimiento de forma sencilla al uso de los recursos en toda su cadena de suministro. En consecuencia, **la presente propuesta se basará en el concepto de exergía como herramienta para la evaluación del nexo agua-energía, permitiendo cuantificar la eficiencia de dichos recursos en toda su cadena de suministro**.

1.5 Estudios de nexo agua-energía en Chile

Actualmente, existen varias limitaciones en la implementación del nexo, particularmente para América Latina y el Caribe (ALC). Mahlknecht et al., (2020) señalaron que no hay conocimiento suficiente de la dinámica del nexo a nivel local, existe falta de información (limitada, fragmentada, incompleta y poco confiable) y la mayoría de los estudios están desconectados o abordan interrelaciones parciales entre los recursos en el nexo. Por otra parte, la dinámica del WEN presenta una dependencia multifactorial e influenciada por características locales. En otras palabras, la intensidad del nexo agua-energía puede intensificarse en función de la variabilidad climática, la disponibilidad y calidad del agua, las diferencias en los usos y la demanda del agua y energía, las características socio-económicas, los avances tecnológicos (eficiencia hídrica y energética) y las políticas relacionadas a la gestión de ambos recursos. Por lo tanto, es necesario desarrollar un enfoque integral en el pensamiento nexo a nivel nacional y regional para proporcionar información confiable sobre el estado del nexo, identificando oportunidades potenciales que podrían contribuir a implementar soluciones factibles que garanticen la seguridad hídrica y energética o la eficiencia de la gestión de los recursos naturales.

Se han realizado algunos esfuerzos en Chile para evaluar y proporcionar evidencia del nexo en diferentes contextos. Particularmente, en el nexo agua-energía se ha abordado a meso y macro-escala el suministro de electricidad, la producción de agua, la provisión de alimentos y otras actividades económicas de relevancia para la economía nacional. Arce et al., (2019) Bórquez and Fuster, (2021) y Peña, (2018) indicaron el consumo de agua y energía en las actividades mineras, agrícolas, servicios sanitarios y generación de electricidad basándose en macro-indicadores cuantitativos o análisis cualitativos. También, Meza et al., (2015) y Ponce-Oliva et al., (2021) desarrollaron modelos matemáticos para simular la disponibilidad de ambos recursos en estas actividades bajo diferentes escenarios de gestión (Suárez et al., 2014). Si bien, estos autores emplearon herramientas cuantitativas para contabilizar la demanda, sus estudios hicieron énfasis en proponer estrategias de gestión basados en aquellos factores que afectan el nexo en regiones o cuencas de Chile donde el agua y la energía se encuentran bajo fuertes presiones, como las situadas en el norte-centro del país. Estos autores señalan que los factores con mayor incidencia en el nexo son la variabilidad climática, la geografía, la demografía, las políticas en vigencia y la modernización tecnológica. Sobre la base de lo anterior, las estrategias de gestión integran cambios en las políticas hídricas y energéticas, así como medidas tecnológicas o económicas, como el amplio uso de la desalinización y reutilización de aguas, cuando son integradas con las energías renovables, y un mercado del agua jerarquizado según la importancia de los sectores productivos en el desarrollo social, respectivamente.

Por otra parte, otros autores se dedicaron a describir una actividad productiva y cómo sus regulaciones inciden en el nexo. Kelly and Negroni, (2020) y Vergara et al., (2017) estudiaron cómo la hidroelectricidad interactúa con el medio ambiente y la sociedad. Estos exponen cómo las regulaciones de instituciones asociadas al agua y la energía causan conflictos entre los pequeños proyectos hidroeléctricos y las poblaciones indígenas (mapuches) por el uso del territorio. Estos estudios demuestran que el nexo agua-energía no necesariamente será más sostenible con una mayor integración institucional.

No obstante, podría decirse que no se ha estudiado a profundidad el sector energético y la potabilización de agua, específicamente la generación de electricidad y producción de agua potable, teniendo en cuenta todas sus tecnologías de generación. Además, estos trabajos solo han estudiado algunas regiones de Chile y se han focalizado en los flujos directos, lo que dificulta tener una perspectiva más diversa del nexo que, como los autores afirman, varía según las características geográficas y las actividades socio-económicas locales.

De otro modo, no se ha considerado la eficiencia del nexo, ni tampoco se ha considerado los recursos acumulados durante la cadena de suministro durante la producción de agua y energía. Tampoco se ha estudiado la evaluación del nexo a escala sectorial considerando toda la matriz eléctrica nacional y el sistema de potabilización de agua urbana. En consecuencia, **la presente propuesta tomará como casos de estudios los sistemas de potabilización de agua y producción de electricidad en Chile para ser evaluados desde la perspectiva de nexo agua-energía, cuantificando la eficiencia en su uso por toda la cadena de valor.**

1.6 Elementos críticos en la evaluación del nexo

En función de lo discutido anteriormente, existen varios elementos críticos en la evaluación del nexo agua-energía que aún siguen sin resolverse:

a) La mayoría de estudios tienen un alcance limitado y una diversidad de métricas que dificulta la comparación y/o replicabilidad de los resultados a diferentes casos de estudio.

b) La calidad del nexo agua-energía, orientada a la eficiencia en el uso de los recursos es un tema sin estudiarse a profundidad.

c) Son escasos los trabajos en el contexto de Chile que abordan el pensamiento nexo en diferentes dimensiones y casos de estudio que permitan proporcionar información confiable sobre el estado del nexo a escala nacional y regional.

d) Si bien los pocos trabajos realizados en Chile abordan y señalan la provisión de agua y energía (sector energético y sanitario) como aspecto crítico del nexo debido a las condiciones climáticas, económicas y políticas locales, todavía no existen estudios que hagan un seguimiento exhaustivo del uso del agua y la energía por la cadena de suministro de la electricidad y el agua potable a nivel nacional. Tampoco existen evidencias del uso de la exergía como métrica para evaluar su eficiencia.

Capítulo 2

Evaluación exergética del nexo agua-energía

2.1 El suministro eléctrico y de agua potable en Chile como casos de estudio

En este capítulo se presentan los casos de estudio seleccionados para evaluar el nexo agua-energía (WEN) mediante herramientas basadas en el concepto de exergía, como el análisis exergético e indicadores que abarcan toda la cadena de valor de un producto.

El primer caso de estudio, relacionado al Sistema Eléctrico Chileno (CES) se ubica en la *línea agua para energía* y se consideró las interdependencias entre los recurso agua-energía y también el recurso suelo. En este caso, se evaluó la eficiencia del nexo en el CES mediante la integración del análisis de ciclo de vida con el análisis de exergía. Los indicadores Consumo Acumulado de Exergía (CExC) y Grado Acumulado de Perfección (CDP) se utilizaron para cuantificar la demanda de recursos naturales en la provisión de electricidad, así como evaluar la eficiencia en su uso. Específicamente, el CExC cuantificó el consumo directo de agua, energía y suelo de las tecnologías de generación eléctrica que constituyen el CES, además de su consumo indirecto debido a la cadena de valor (extracción, procesamiento y transporte) de los combustibles que las abastecen. El CDP, al enfocarse en la eficiencia en el uso de los recursos naturales, se consideró en este estudio como una medida de la calidad del WEN en el suministro eléctrico. Este estudio demostró la viabilidad del concepto de exergía en la evaluación del nexo agua-energía y en cualquier tipo de nexo que incorpore recursos naturales, ya que provee herramientas que pueden cuantificarlos bajo una misma métrica. Por lo tanto, podría facilitar la comparación entre procesos y la integración de escalas (procesos, sectorial y áreas geográficas).

Por otro lado, el segundo caso de estudio está dentro de la *línea energía para agua.* Similar al estudio anterior, se evalúa el WEN en la cadena de suministro de agua potable en Chile mediante el Análisis de Ciclo de Vida Exergético (ELCA). En el CExC se cuantificó el consumo de exergía acumulado atribuido al agua dulce y la energía demandada por las tecnologías de potabilización durante todo el ciclo de vida, considerando para el recurso energía el valor del CExC estimado para el CES. En este indicador se evidenció cómo la intensidad energética de las tecnologías varía según las condiciones geográficas; también resalta los recursos hídricos en el nexo en términos de disponibilidad y disposición por regiones mediante los indicadores WSI y BWF.

En las secciones siguientes, 2.2 y 2.3 se especifican con mayor detalle la implementación de las herramientas exergéticas en la evaluación del WEN en los casos de estudio mencionados.

2.2 Evaluación del Nexo Agua-Energía-Suelo (WELN) usando indicadores basados en la exergía: El caso del Sistema Eléctrico Chileno

Publicado en la revista *Energies:* Rodríguez-Merchan et al., (2020)**.** Evaluation of the Water-Energy-Land Nexus (WELN) using exergy-based indicators: The chilean electricity system case. *Energies* **2020**, *13* (1), 42.

Abstract: The competition and interlinkages between energy, water, and land resources are increasing globally and are exacerbated by climate change and a rapid increase in the world population. The nexus concept has emerged for a comprehensive understanding related to the management and efficiency of resource use. This paper assesses water–energy–land nexus (WELN) efficiency through integration of the principles of Life Cycle Assessment (LCA) and exergy analysis, using the Chilean Electric System (CES) as a study case. The cumulative exergy consumption (CExC) and cumulative degree of perfection (CDP) are used as indicators for WELN efficiency. The results show the production of 1 MWh of electricity required 17.3 GJ_{ex}, with the energy component of WELN (fossil and renewable energy sources) being the main contributor (99%). Furthermore, the renewable energy technologies depicted higher CDP of the water–energy–land nexus due to lower CExC and higher technology efficiency concerning non-renewables. The water and land resources contributed slightly to total exergy flow due to low quality in comparison with the energy component. Nevertheless, water availability and competition for land occupation constitute important issues for reducing environmental pressures and local conflicts. This study demonstrated the feasibility of exergy analysis for the evaluation of WELN efficiency through a single indicator, which could facilitate the comparison and integration with different processes and multi-scales**.**

Keywords: water–energy–land nexus; exergy analysis; Chilean Electric System; exergy efficiency

1. Introduction

The faster growth of world population, urbanization and anthropogenic activities contributes to increasing the demand and pressure for natural resources, especially on energy, water, and land (Guan et al., 2019).

Nowadays, the interdependence of energy, water and land demand requires a new methodological framework for a better understanding of interactions between resources (Guan et al., 2019). In this context, the nexus thinking has emerged as a holistic and comprehensive framework, allowing an improvement of resource use efficiency (Brouwer et al., 2018) and avoiding future pressures on natural resources (Ibrahim et al., 2019). The majority of nexus studies have been focused on the water production and treatment systems (wastewater and drinking water treatment processes) (Lee et al., 2017). Other studies have been extended the scope of energy-water nexus, including the interactions with agriculture and food security (Bazilian et al., 2011).

In recent years, analyzing issues associated with the water–energy–land nexus (WELN) of anthropogenic systems has increasingly gained interest by both scientists and government decision makers (Cremades et al., 2019a; Cremades and Sommer, 2019b; Nie et al., 2019). The inclusion of land on the water and energy nexus is justified by its relevant interactions with other productive sectors, which cannot be ignored (Ibrahim et al., 2019). Although the WELN have been analyzed in literature, the land resources interaction with water and energy still needs to be studied further.

The nexus concept is an systematic approach for improvement of resource management, which can reach high degrees of complexity depending on scales and processes (Dargin et al., 2020). Consequently, different qualitative and quantitative methods for conceptualizing the relationship between natural resources have been proposed. (Ringler et al., 2013) developed a comprehensive qualitative framework for assessing the water, energy, land and food nexus (WELF), highlighting the relevance of land in the nexus. Nevertheless, the authors did not provide methods for the WELN-nexus evaluation. Siciliano et al. (2017) have recently reported on the effect of large-scale farm investment in the European Union on the water–energy–land–food (WELF) nexus, using indicators related to resource availability, scarcity and access. Although the authors describe several interlinkages between the resources, the quantitative evaluation of the nexus is not clearly highlighted. Karabulut et al. (2018) studied the ecosystem–water–food–land–energy (WFLE) nexus by considering the ecosystem as the main issue within this nexus. The authors highlights the relationship between interventions and environmental impacts. In this case, the nexus evaluation is qualitative, and the matrix proposed can be adapted to different scales to investigate the trade-offs, synergies and antagonisms.

Different approaches have been used to quantitatively evaluate the WELN. Silalertruksa and Gheewala, (2018) carried out the evaluation of the WELN of sugarcane production in Thailand, using water scarcity, carbon and ecological footprint. The authors conclude that the combined use of these footprint indicators can give a quantitative and comprehensive picture of the WELN of agriculture. Moreover, Saif and Almansoori, (2017) presented a discrete optimization model for the Climate, Land, Energy and Water (CLEW) nexus interactions using Mauritius Island as case study. In this study, the mathematical model was applied and used as support in strategic decisions related to energy, water and land systems. Ibrahim et al. (2019) evaluated the efficiency of OECD countries in terms of a Water–Energy–Land–Food (WELF) nexus. An input–output analysis was built at a European level, providing a framework for policy making. Similar analysis was reported by Guan et al. (2019), who studied the main drivers and relationships of WELN in the all Chinese economy supply chain. Results show that agriculture and light industry are critical sectors for water consumption and land occupation; meanwhile, the heavy industry and construction present the highest energy requirements.

From the sustainability energy system point of view, several authors have highlighted that an improvement of energy technology can reduce the trade-offs across the three WELN dimensions (Lechón, 2018; Stigson et al., 2015). Furthermore, it is recognized that to ensure the sustainable use of natural resources within the nexus, the integration of life cycle thinking for preventing the different environmental pressures and impacts on resources during the whole life cycle should be addressed (Karabulut et al., 2018). In this sense, very few studies have integrated the life cycle thinking within the nexus framework (Mekonnen and Hoekstra, 2016; Wang and Chen, 2016).

Most of these studies have a relatively limited scope and focus on the water and energy nexus assessing at sector-based scale, specifically the effect on agriculture. In addition, the reported studies cover different scales and include the development of many tools, indicators and metrics.

Recently, Dai et al., (2018) reported a comprehensive review related to the diversity of methods, tools and frameworks used to evaluate the interactions between several resources (water, energy, food, land, etc.) in the nexus context. Nevertheless, the diversity of metrics limits the comparative experiences and replicability in different contexts and also does not consider the efficiency of resources uses into the nexus (Larsen and Drews, 2019; Shannak et al., 2018). In this sense, the exergy analysis could play an essential role in the evaluation of the nexus, based on their efficiency (Szargut, 2004; Wall and Gong, 2001). Exergy analysis has emerged as a robust methodology for the assessment of natural resources sustainability (Dewulf et al., 2008; Granovskii et al., 2007; Sciubba, 2019, 2018). Also, exergy is a measure of transformation quality of virgin resources used in any technology through cumulative exergy consumption (CExC) and cumulative degree of perfection (CDP) in the Life Cycle Assesment (LCA) methodology (Dewulf et al., 2008, 2000). Therefore, a cumulative exergy approach provides a unified way to assess the consumption of resources with a solid scientific basis and offers a clear vision of the degradation of the natural capital involved through a chain of production. Thus, it could be a useful methodologic approach for a holistic assessment of WELN.

The WELN is strongly dependent on economic structures, technology levels and policy related to resource management. Therefore, the analysis of WELN considering the local circumstances and natural resources efficiency is necessary for supporting the policy-making towards the sustainable use of multiple resources. To the best of our knowledge, the evaluation of nexus lacks a proper method for evaluating WELN efficiency based on exergy principles, allowing a better understanding of how the local resources can be efficiently managed at different scales (process, sector, basin, country).

Therefore, the main objective of this study is to develop a method to assess WELN efficiency, integrating the principles of the Life Cycle Assessment (LCA) and exergy analysis using the Chilean Electric System (CES) as a case study. The exergetic life cycle assessment (ELCA) is used to quantify the indirect exergy inputs associated mainly to water, energy and land resources during the whole fuel life cycle, constituting the basis for the assessment of the efficiency of resources use. The cumulative exergy consumption (CExC) is quantified for evaluating of 1 MWh of electricity during its life cycle. This indicator breaks down into the water, energy and land components. Also, the WELN nexus efficiency is evaluated using the cumulative degree of perfection (CDP), which is heavily dependent on CExC and technology efficiency. The analysis performed constitutes the first approach for quantifying the efficiency of the water–energy–land nexus, which could be an important support for decisio-makers in order to establish policies related to the multiple resources uses sustainability in the territorial planning.

2. Materials and Methods

2.1. System Boundaries and Functional Unit

The Chilean Electric System (CES) was selected as a case study, taking 2017 as the reference year. The CES power plant network covers the Northern and South-Central parts of Chile, extending 3100 km from the Arica-Parinacota region to Chiloé archipelago. The CES provides 99.3% of the electricity generation capacity (~25 GW) of the country, supplying nearly 98.5% of the Chilean domestic electricity demand. The remaining electricity demand (0.7%) is fulfilled by two small grids (Aysen system, Magallanes system) located in the extreme south of Chile, which are not considered in the present study. For 2017, the CES generated approximately 74,304 GWh of electricity, of which 57% came from fossil fuels such as coal, LNG, natural gas and oil products. The rest of the electricity generated (43%) came from renewable energies, such as hydro, solar, wind and biomass (CNE, 2018). The electricity generation at CES (year 2017) is shown in Table 1, as a function of energy sources**.**

Table 1. The Chilean Electric System (CES) electricity generation. Year 2017 (CNE, 2018)**.**

	Type of Energy	**Number of Plants**	**Electricity Generation (GWh)**	**Contribution (%)**
Non-Renewable Energy	Coal	27	28,970	39
	LNG	15	10,233	15
	Natural gas	15	2,460	2
	Diesel	122	400.8	0.5
	Fuel oil	9	47	0.06
	Petcoke	1	436	0.6
Renewable Energy	Hydro	172	21,728	29
	Solar	97	3,869	5
	Wind	28	3,389	5
	Biomass	36	2,770	4
Total		522	74,304	100

In this study, the water–energy–land nexus is assessed by integrating the principles of the Life Cycle Assessment (LCA) and exergy analysis. In our case, the functional unit and system boundaries were defined based on the framework of LCA. The exergetic life cycle assessment (ELCA) is used to quantify the indirect exergy inputs associated mainly to water, energy and land resources during the whole fuel life cycle.

The water–energy–land nexus for CES was evaluated using the cradle-to-gate system boundary approach. In this case, the extraction, processing and transport of fossil fuels, as well as the electricity generation at the CES system gate, were considered. The stages related to the technologies manufacturing and the electricity transmission system was not considered in the present study. The non-renewable technology manufacturing was excluded due to negligible impacts of resources concerning to operational phase (Paletto et al., 2019; Turconi et al., 2013). In contrast, the manufacturing of renewable technologies is significant in resource consumptions (Karlsdottir et al., 2020), which heavily relies on the materials origin, energy used for the infrastructure and technological characteristics (Turconi et al., 2013). However, due to the lack of information for materials origin and technologies, the renewable technologies manufacturing was excluded from the present analysis. Furthermore, there are no data available for the transmission system, specifically for accounting the land resources; thus, the same assumptions as Lechón et al. (2018) were considered to exclude this item from the analysis.

The processes were classified into two subsystems, the background and the foreground, respectively. The background system included the freshwater (W_I), energy (E_I) and land (L_I) consumed and used indirectly for the production of fossil fuels life cycle (extraction, processing and transport), which are fed to CES. The foreground system considered the water (W_D), energy (E_D) and land (L_D) consumed and used directly by CES, as well as the indirect inputs coming from the background system. The functional unit (Fu) was chosen as 1 MWh of electricity to the gate of the electricity system. The cradle-to-gate system boundaries for electricity generation provided by CES are shown in Figure 5.

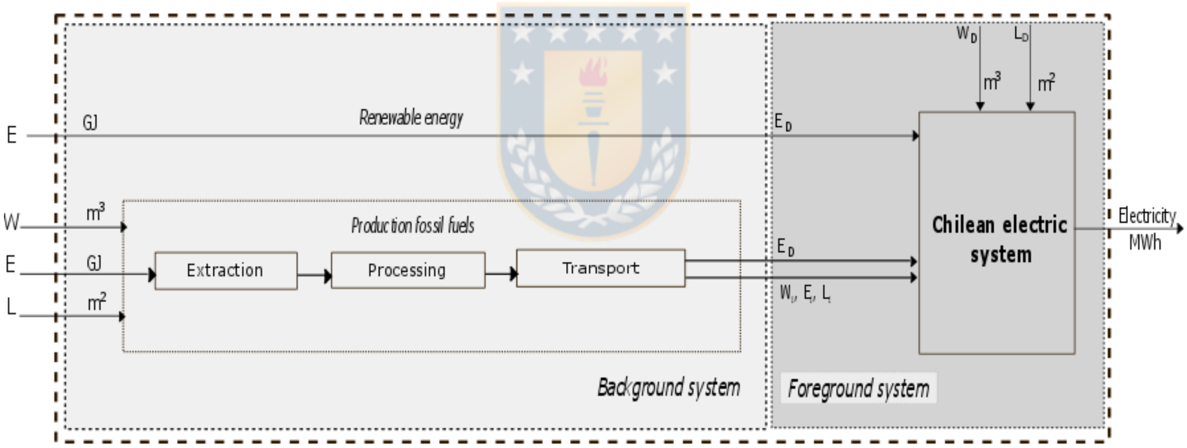

Figure 5. System boundaries for the CES**.**

2.2. Material Exergy Fluxes

The freshwater, energy and land demanded and used in the system are accounted for exergy (GJ_{ex}). Exergy is defined as the maximum work that can be delivered by the component of the system in relation to the reference environment. The reference state is defined by a temperature of T_o = 298.15 K, pressure P = 1.01 bar, and the atmosphere composition (Szargut, 2005).

In this study, the exergy of the material fluxes (freshwater and fuels) are estimated as the sum of physical (Ex_{ph}), chemical (Ex_{ch}), kinetic (Ex_k) and potential (Ex_p) components, and the balance can be written as (J. Szargut, 2005):

$$\mathrm{Ex} = \mathrm{Ex_k} + \mathrm{Ex_p} + \mathrm{Ex_{ph}} + \mathrm{Ex_{ch}}, \tag{1}$$

The electrical exergy is considered equal to its the energy content (Dincer and Rosen, 2007; Szargut, 2005). In the case of thermal power plants, the chemical exergy of direct and indirect inputs of freshwater and fuels (diesel, coal, natural gas, petcoke and fuel oil) are only considered, since the physical, kinetic and potential interactions concerning the reference environment are negligible. The chemical exergy component of fuels and freshwater was estimated following Equation (2) (Szargut, 2005).

$$\mathrm{Ex_{ch}} = \mathrm{Ex_i^0} \times \mathrm{m_i}, \tag{2}$$

where $\mathrm{Ex_{ch}}$ represents the chemical exergy content of *i* material (freshwater and fuels) in terms of $\mathrm{GJ_{ex}}$. The $\mathrm{Ex_i^0}$ ($\mathrm{GJ_{ex}}$/t) and $\mathrm{m_i}$ (t/yr) are the standard chemical exergy and the resource consumptions, respectively. The standard chemical exergy of fuels (except coal) and freshwater are gathered from Szagurt, (2005) and are listed in Table 2.

The standard chemical exergy of coal was calculated by multiplying the lower heating value (LHV) by the exergy factor β. The β-value is the exergy-to-energy ratio and depends on the atomic composition of the fuel (Szargut, 2005).

$$\mathrm{Ex_i^0} = \mathrm{LHV} \times \beta, \tag{3}$$

$$\beta = 1.0437 + 0.1896\frac{\mathrm{Z_H}}{\mathrm{Z_C}} + 0.0617\frac{\mathrm{Z_O}}{\mathrm{Z_C}} + 0.0428\frac{\mathrm{Z_N}}{\mathrm{Z_C}},\ \text{para}\ \left(\frac{\mathrm{Z_O}}{\mathrm{Z_C}} \leq 0.667\right), \tag{4}$$

Here, Zi is the mass fraction of each component involved in coal characterization (ultimate analysis), and the LHV corresponds to coal lower heating value. The coal used in CES is characterized by 73.7% of carbon, 8.7% of oxygen, 5% of hydrogen and 1.3% of nitrogen and the LHV of 28,700 MJ/t (Cerrejon, 2017).

Table 2. Standard chemical exergy of water and energy resources.

	Resources	Standard Chemical Exergy	Unit	Reference
Energy	Coal	30.5	GJ_{ex}/t	-
	Diesel	44.7	GJ_{ex}/t	(Szargut, 2005)
	Natural gas	0.10	GJ_{ex}/MJ	(Szargut, 2005)
	Petcoke	29.9	GJ_{ex}/t	(Szargut, 2005)
	Fuel oil	47.1	GJ_{ex}/t	(Szargut, 2005)
Water	Freshwater	5×10^{-11}	GJ_{ex}/m^3	(Szargut, 2005)

For renewable technologies (hydraulic turbines, wind turbines and solar photovoltaic panels), the kinetic, potential and physical exergies are calculated. The primary expression used for each technology is described below.

The kinetic exergy (Ex_K) component was considered for wind turbines, which is estimated according to Aghbashlo et al. (2018):

$$Ex_K = \frac{1}{2}\dot{m}v^2t, \tag{5}$$

where Ex_k is the kinetic exergy in terms of GJ_{ex}. $\dot{m}$ (kg/s) and v (m/s) correspond to mass and speed flows of air. The term t is the time referred to a yearly base. The parameter $\dot{m}$ is determined based on technical parameters that characterized the technology (surface area, density and stream speed).

The potential exergy (GJ_{ex}) is also quantified for hydraulic turbines, and it is calculated by Equation (6):

$$Ex_p = \dot{m}ght, \tag{6}$$

where $\dot{m}$ represents the mass flow, g gravitational acceleration (9.8 m/s^2), t is operation time of the process, h the difference in levels in hydropower plants. The level differences were based on the operational characteristics of each hydropower plant. For run-of-river hydroelectric, the h was assumed 4–1100 m. In the case of reservoir hydroelectric, values were between 50–545 m. The annual average streamflow was taken for each hydropower plant design, which was obtained as a result of the flow duration curve method (Ridolfi et al., 2018; Rugumayo and Ojeo, 2006). Specifically for hydroelectricity, with installed power below 100 MW, the daily streamflow was measured over 30 years; meanwhile, the time resolution of 50 years was considered for installed power above 100 MW. For each specific hydropower plant involved in CES, the hydropower energy potential, net water head and streamflow were taken from primary data available in National Environmental Declaration System (SEIA, 2018).

The photovoltaic panels only involved the physical exergy component, which is calculated according to the Equation (7) (Zuhur et al., 2019):

$$\mathrm{Ex_{ph}} = \mathrm{R_S}\left(1 - \frac{\mathrm{T_{env}}}{\mathrm{T_{sun}}}\right) \mathrm{a\ t}, \tag{7}$$

where $\mathrm{Ex_{ph}}$ is the physical exergy ($\mathrm{GJ_{ex}}$). The $\mathrm{R_S}$ (W/m) and $\mathrm{T_{env}}$ (K) are the average annual solar radiation and environmental temperature, respectively. The $\mathrm{R_s}$ and $\mathrm{T_{env}}$ were based on regional climate variables as a function of actual power plant localization, which was taken from Santana et al. (Santana et al., 2014). The $\mathrm{T_{sun}}$ represents the sun temperature (5778 K), t is operation time in a year, and a is the panel area. For all solar photovoltaic panels, the area was taken as 1.7 $\mathrm{m^2}$ (Santana et al., 2014).

2.3. Exergy Component of Land Resource

The land occupation associated with background and foreground systems in terms of exergy units ($\mathrm{GJ_{ex}}$) was quantified, as depicted in Equation (8). This method was proposed by Taelman et al. (2016) and based on landcover class and the land surface occupied by technologies. The authors provided a spatial differentiation of the characterization factor (net primary productivity (NPP)), expressed in exergy terms ($\mathrm{MJ_{ex}/m^2.year}$) for 40 land use types (e.g., urban land, grasslands-high livestock density, forest-with agriculture activities, agriculture, et al.) at the continent, country and region levels, including Chile.

The indicator proposed by Taelman et al. (2016) was based on the integration of potentialities of NPP and exergy analysis as a proxy indicator of the ecosystem functioning. The NPP is commonly used for representing the resilience and functionalities of ecosystems, the buffering capacity and absorption ability of wastes and emissions (Taelman et al., 2016), as well as the supply of products and services to humans (Erb et al., 2009; Millennium Ecosystem Assessment, 2005). Besides, exergy is a thermodynamic model which has emerged as an indicator for accounting the natural resources efficiency. Exergy reflects the physical and chemical potential and usefulness of resources (matter and energy), but also providing a more holistic characterization of any system involving matter transformations such as the ecosystems (Rosen and Dincer, 2001; Bilgen and Sarikaya, 2015)

The NPP-based exergy constitutes a measure of intensity and the efficiency at which each hectare of land is used (Alvarenga et al., 2013b, 2013a; Martínez et al., 2019; Taelman et al., 2016). The exergy component of land resource can be estimated according to Equation (8):

$$\mathrm{Ex_L} = \mathrm{CF} \times \mathrm{S}, \tag{8}$$

where CF (GJ_{ex}/m^2.year) represents the characterization factor reported by Taelman et al., (2016), who provided the land-based exergy indicators by countries and land use types, and S (m^2) the land surface occupation. The land occupation factors for each technology are specified in section 2.3. The characterization factors (GJ_{ex}/m^2.year) values for land occupation associated with the foreground system (direct land input) were chosen as urban/industrial land use (0.003 GJ_{ex} /m^2 year) specified for Chile. Meanwhile, for the indirect land use related to the background system, specifically for non-renewable energy, the land use characterization factor was assumed in a function of origin fuels, considering that oil and natural gas came from the United States (0.011 GJ_{ex} /m^2 year), as well as the coal from Colombia (0.012 GJ_{ex} /m^2 year).

2.4. Exergetic Index

The water–energy–land nexus assessment was carried out using two exergy-based indicators, such as cumulative exergy consumption (CExC) and cumulative degree of perfection (CDP)

(Dincer and Rosen, 2007; Huysveld et al., 2015). The CExC and CDP were defined for each type of resource and energetic technology.

The life cycle exergy demand for the production of 1 MWh (Fu) of electricity coming from CES, the CExC ($\mathrm{GJ_{ex}}$/MWh), is defined as the sum of exergy content of all resources required to provide it, considering the extraction, processing and transport stages. This study is focused on direct and indirect exergy inputs of freshwater, energy and land resources. Equation (9) was taken from Dincer and Cengel, (2001) and specified in Equation (7):

$$\mathrm{CExC}_{k} = \frac{\sum_{\mathrm{i,j}}\left(\mathrm{Ex}_{\mathrm{E}_{\mathrm{i,j}}}+\mathrm{Ex}_{\mathrm{W}_{\mathrm{i,j}}}+\mathrm{Ex}_{\mathrm{L}_{\mathrm{i,j}}}\right)}{\mathrm{Fu}}, \tag{9}$$

where $\mathrm{Ex_E}$ ($\mathrm{GJ_{ex}}$), $\mathrm{Ex_W}$ ($\mathrm{GJ_{ex}}$), $\mathrm{Ex_L}$ ($\mathrm{GJ_{ex}}$) are the exergetic contents of energy, freshwater and land. The subscripts i and j refer to indirect and direct inputs (freshwater, energy and land use). The k represents the technology type.

The CDP (%) represents the life cycle exergy efficiency of the whole electricity system (Equation (10)) (Huysveld et al., 2015; Szargut, 2005). It is defined as the ratio between the electricity produced ($\mathrm{Ex_{el}}$ = 1 MWh) and the exergy content CExC ($\mathrm{GJ_{ex}}$/MWh) of all resources consumed, directly and indirectly, making emphasis on freshwater, energy and land resources.

$$\mathrm{CDP}_{k} = \frac{\mathrm{Ex_{el}}}{\mathrm{CExC}_{k}} \times 100, \tag{10}$$

2.5. Data Sources

Primary data related with the foreground system (CES) was gathered on-site, coming from 527 power plants existing in the country and complemented with bibliographic sources. The primary data corresponds to energy efficiency, fossil fuel consumption and electricity generation for each technology available in CNE, (2018).

The freshwater consumptions used in thermal power plants for cooling systems were completed using factors reported by OECD-IEA, (2016). The thermal power plants that consumed sea water for cooling were not considered in the nexus interactions. For that reason, only 31 combined cycle power plants of the total (225) were included for the accounting of freshwater demand, which represents 16% of total electricity generated by CES. The direct freshwater consumption factors were based on cooling systems (7 m^3/MWh for the wet tower and 5 m^3/MWh for once-through cooling), independently of fuel types (OECD-IEA, 2016).

The land occupation for renewable energy technologies (solar photovoltaic panels, wind turbines and biomass-thermal power plant) was obtained from Santana et al. (2014). In the case of hydro and thermal power plants (coal, diesel, natural gas), the land surface occupation was estimated based on the actual location using satellite imagen provided by google earth. In the present study, the land occupation was differentiated by reservoir and run-of-river hydropower plants. Specifically for run-of-river hydro, the land occupation factor was assumed the same for all hydropower plants due to the lack of information, which was gathered from Santana et al. (2014). The factor value was 257 m^2 per installed capacity (MW). In the case of the reservoir, the land occupation factor was considered as an average value estimated for all hydropower plants involved in CES, which varies from 3121 and 4173 m^2/MW. The average land occupation factor (3824 m^2/MW) was estimated as a relationship of surface area occupied by each reservoir and its respectively installed power. The specific freshwater consumptions and land occupation by each technology are gathered from OECD-IEA (2016) and Santana et al. (2014).

The secondary data of the background system were taken from the Ecoinvent v 2.1 database (Ecoinvent, n.d.). This database involves a set of input and output data information on specific processes, and it is typically used for the background data where the information is not available. Furthermore, Ecoinvent is recognized and accepted as leading life cycle inventory database due to its consistency and transparency of the data. The energy and water consumption, as well as land occupation, for the production of fossil fuels (extraction, processing and transport) were estimated using specific consumption and occupation factors available in the mentioned database.

3. Results

3.1. Cumulative Exergy Consumption (CExC) Analysis

The cumulative exergy consumption demanded (CExC) by type of technology and energy resources for CES is depicted in Figure 6. The result shows that 17.3 GJex (CExC) are required for producing 1 MWh of electricity in the CES. In this context, non-renewable energies represent higher resource consumption (11.5 GJ$_{ex}$/MWh) than renewable energy, representing 67% of the total CExC of CES. The steam turbine is the most dominant technology in the CES, demanding 9.2 GJ$_{ex}$ of resources by each 1 MWh of electricity, with coal and biomass being the main fuels. The coal shows the highest contribution in CExC (7.8 GJ$_{ex}$/MWh), as 46% of the total (17.3 GJ$_{ex}$/MWh), followed by combined cycles fueled with LNG (14.7%), hydropower plant (13.2%) and solar photovoltaic (8.3%). The biomass steam turbines (1.1 GJ$_{ex}$/MWh), wind turbine (1.0 GJ$_{ex}$/MWh) and natural gas used in turbines and combined cycle (0.8 GJ$_{ex}$/MWh) also play an essential role in the total CExC (16.5%). Meanwhile, the fuel oil Nº6, petcoke and diesel have a negligible contribution to total consumed resources, representing only 1.4%.

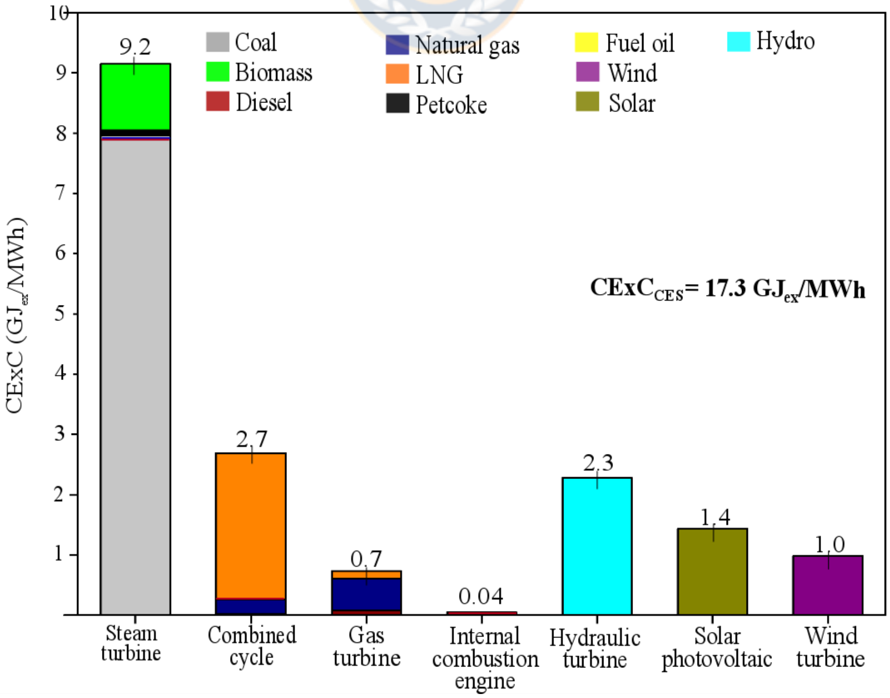

Figure 6. Total demanded resources (CExC) of CES distributed by energy sources and technologies.

Figure 7 reports the total embodied energy, water and land used for the generation of 1 MWh of electricity coming from CES. Results are presented on the basis of the exergy-based indicator CE*x*C. As can be seen, the resource distribution exhibit significant disparities, with the energy resources being the most dominant (99.7% of total Ce*x*C) in the nexus. Meanwhile, the water (0.2%) and land (0.1%) components are negligible. In addition, the direct and indirect exergy consumptions associated mainly with energy, water and land are also depicted in Figure 7. The indirect component is referred to as all energy, water and land consumed during the whole life cycle (extraction, processing and transport) of fuels (background system). Meanwhile, the direct component involves the energy, water and land consumed directly in the foreground system, which corresponds to the Chilean Electricity System (See Figure 7).

In this sense, the direct exergy consumption for energy and water resources is dominant in comparison with the indirect component, representing 67% and 88 % of total CexC of each resource, respectively. Instead, the indirect exergy consumption (93%) shows a higher contribution than direct components (7%) for land use.

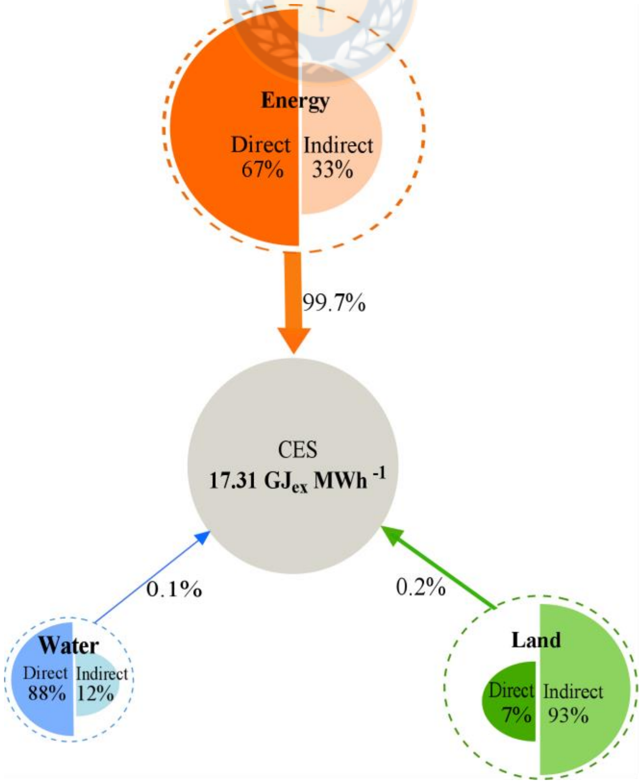

Figure 7. Contribution of energy, water and land resources in CexC of CES.

A detailed analysis of direct and indirect components of CExC for the different energy types segregated by energy, water and land resources are shown in Table 3. Non-renewable energy sources included direct and indirect exergetic components. In contrast, renewable energy sources only involve direct exergy consumption. The coal represents the highest contribution in terms of CExC (7.9 GJex/MWh), followed by LNG (2.6 GJex/MWh) and hydro (2.3 GJex/MWh). The solar (1.4 GJex/MWh), biomass (1.1 GJex/MWh) and wind (1.0 GJex/MWh) also depicted essential contributions. Nevertheless, the diesel, petcoke and fuel oil showed the lowest cumulative exergy consumption, reporting values below 0.1 GJex per MWh of electricity.

For non-renewable energy sources, coal is the fuel with the highest share into the nexus (7.9 GJex/MWh), representing 69% of the total for non-renewables. In this case, the direct (4.2 GJex/MWh) exergy demand for the energy resource is higher than indirect (3.6 GJex/MWh). Meanwhile, the indirect inputs related to energy resources for diesel, natural gas and LNG are higher in comparison with the direct component, representing 80%, 50% and 55% of total CExC by each resource, respectively.

Table 3. Direct and indirect exergetic consumption for different energy types and resources (water, energy and land).

	Type of Energy	**CExC (GJex/MWh)**	**Direct Input (GJ_{ex} /MWh)**			**Indirect Input (GJ_{ex}/MWh)**		
			Energy	**Water**	**Land**	**Energy**	**Water**	**Land**
Non-Renewable Energy	Diesel	0.1	0.06	1.2×10^{-15}	1.1×10^{-4}	0.07	3.5×10^{-13}	6.2×10^{-5}
	Natural gas	0.8	0.3	0	9.8×10^{-5}	0.4	1.2×10^{-13}	1.9×10^{-4}
	LNG	2.6	1.1	4.5×10^{-11}	1.0×10^{-4}	1.44	4×10^{-13}	6.2×10^{-4}
	Fuel oil N°6	0.01	0.01	0	0	0.01	3.3×10^{-14}	6.1×10^{-6}
	Coal	7.9	4.2	0	6.1×10^{-4}	3.6	6.9×10^{-12}	3.8×10^{-2}
	Petcoke	0.1	0.07	1.1×10^{-11}	8.9×10^{-6}	0.02	9.5×10^{-14}	1.9×10^{-5}
	Total	11.5	5.8	5.7×10^{-11}	9.4×10^{-4}	5.6	7.9×10^{-12}	3.9×10^{-2}
	Contribution (%)	67	34	3.3×10^{-10}	5.4×10^{-3}	33	4.5×10^{-11}	0.2
Renewable Energy	Solar	1.4	1.4	0	1.3×10^{-3}	0	0	0
	Wind	1	0.9	0	1.1×10^{-4}	0	0	0
	Hydro	2.2	2.2	0	3.1×10^{-3}	0	0	0
	Biomass	1.1	1.1	0	4.7×10^{-5}	0	0	0
	Total	5.8	5.8	0	4.6×10^{-3}	0	0	0
	Contribution (%)	33	32.7	0	2.6×10^{-2}	0	0	0

3.2. Water–Energy–Land Nexus Efficiency

The water–energy–land nexus efficiencies for the type of technologies and energy resources involved in CES, as well as the average CDP by groups of technologies, are reported in Figure 8. The CDP parameter is scaled between zero and one, where zero means low efficiency of resources transformation towards products, while values near 100% mean that all resources are transformed efficiently into products. The CDP accounts how most efficiently are used the resources in the process.

The CDP for hydraulic turbines accounts for an average of 46%, being the highest exergy efficiency in comparison with the rest of the technologies. The average of CDP for the rest of technologies varies between 13% and 19%, with solar photovoltaic (13%) and gas turbines (14%) being the technologies with lower efficiencies. The combined cycle efficiency takes values of 19%; meanwhile, the steam turbines, internal combustion engines and wind turbines depicted similar averages of CDP (17%). For non-renewable technologies (steam and gas turbines, combined cycle and internal combustion engines), the CDP also varies with energy resource types (coal, diesel, biomass, et al.).

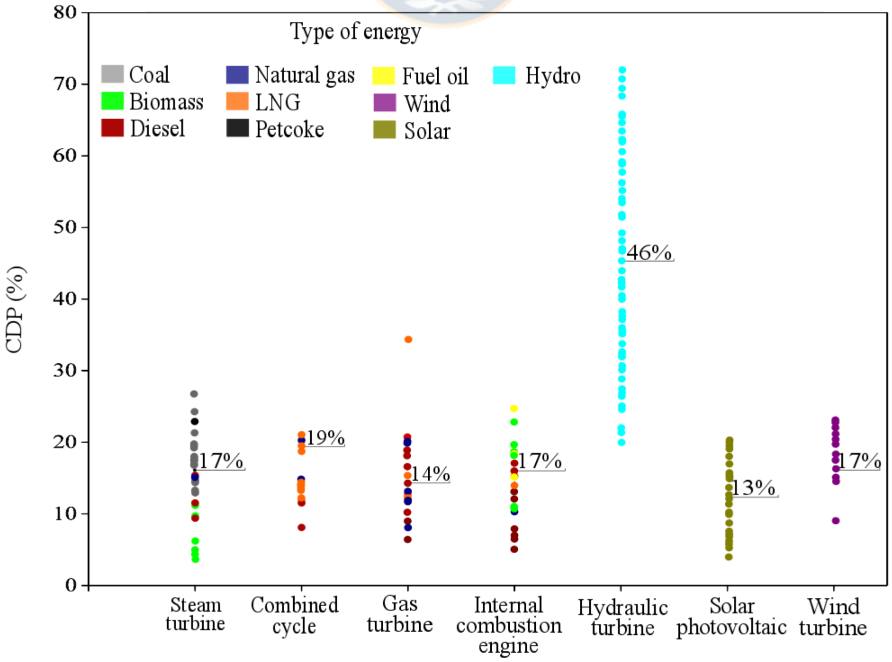

Figure 8. Cumulative degree of perfection (CDP) for each energy technology as a function of energy types.

Figure 9 a, b, c illustrates the water–energy–land nexus assessment. It was carried out through a correlation between CDP and CExC by each resource (water, energy and land) and type of technology. The pattern shown for CExC of energy represents a homogenous distribution concerning CDP. The hydropower plants (reservoir and run-of-river hydro) show the highest CDP (28%–72%) and lowest $\mathrm{CExC_{energy}}$ (8–12 $\mathrm{GJ_{ex}}$/MWh). In contrast, the lower efficiency and higher $\mathrm{CExC_{energy}}$ are depicted for steam turbines and solar photovoltaic, where the CDP and CExC take values below 15% and above 40 $\mathrm{GJ_{ex}}$/MWh, respectively. Regarding patterns obtained for water (Figure 9b) and land (Figure 9c) resources, significant disparities were obtained. The non-renewable technologies are the most intensive regarding water demand within the CES, depicting CDP in the ranges of 8%–23%. Nevertheless, the total demanded water ($\mathrm{CExC_{water}}$) varies by technologies. In this case, the majority of combined cycle power plants involved in CES demands higher water accounting for 3.5×10^{-10} $\mathrm{GJ_{ex}}$/MWh, followed by internal combustion engines ($1–1.8 \times 10^{-10}$ $\mathrm{GJ_{ex}}$/MWh). According to Figure 9c, all the technologies are dependent on territory uses. In this sense, a significant number of steam turbines power plants present higher use of land in comparison with the rest of energy production technologies, taking values of $\mathrm{CExC_{land}}$ 0.1–0.15 $\mathrm{GJ_{ex}}$/MWh. In general, the non-renewable technologies depicted the lowest CDP and $\mathrm{CExC_{land}}$. Comparable performance in terms of CDP is also shown by solar photovoltaics, accounting for higher $\mathrm{CExC_{land}}$ (0.3–0.1 $\mathrm{GJ_{ex}}$/MWh) concerning non-renewable technologies (<0.3 $\mathrm{GJ_{ex}}$/MWh). Meanwhile, the hydropower plants (run-of-river and reservoir) show similar CDP (25%–70%), but the $\mathrm{CExC_{land}}$ was different by each technology. The run-of-river power plant (0.01 $\mathrm{GJ_{ex}}$/MWh) shows lower $\mathrm{CExC_{land}}$ than reservoir hydropower plants (0.05 $\mathrm{GJ_{ex}}$/MWh).

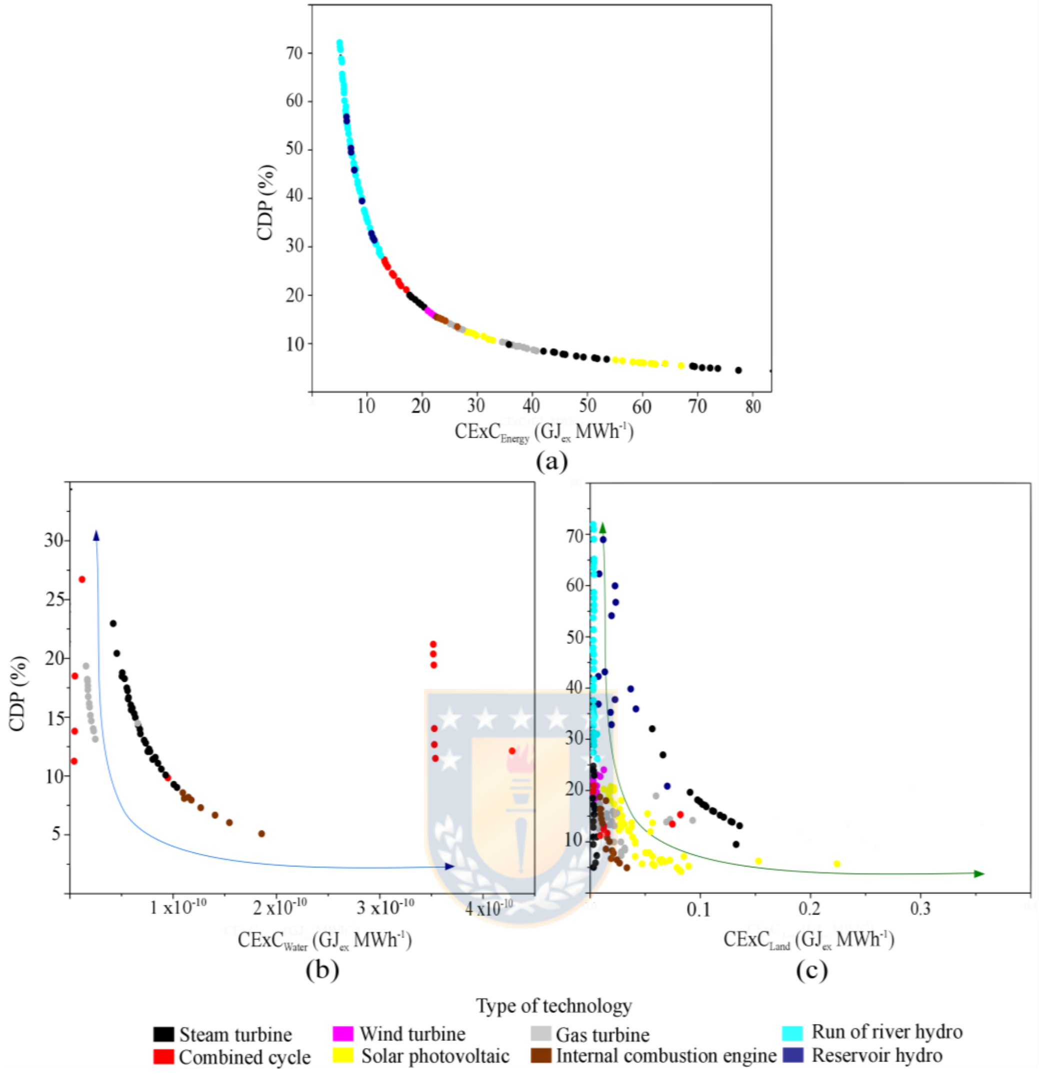

Figure 9. Correlation between CDP and CExC each resources and by type of technology. The specifically CExC for energy resource is depicted in (**a**); The CExC for water and land resources are shown in (**b**) and (**c**), respectively.

4. Discussion

4.1. Cumulative Exergy Consumption (CExC) Analysis

The CES showed high cumulative exergy consumptions per MWh of electricity (17.31 GJex/MWh), which is significantly higher than reported by China (10.8 GJex/MWh) (B. Zhang et al., 2018) and Brazil (8.6 GJex/MWh) (Mosquim et al., 2018). The significant differences found here are associated with the fuel contributions to the electricity matrix of each country. Accordingly, higher CExC is expected for higher shares of fossil fuel in the energy sector. Specifically for China, the electricity matrix is dominated by thermal power plants fed by coal, representing 79% of total power generation. In contrast, the Brazilian electricity sector is based on hydropower plants (68% of total), where fossil fuels only share 9%. In the Chilean case, 57% of electricity generated comes from fossil fuels (coal and natural gas), which is lower than in China and higher concerning Brazil.

Nevertheless, the present results could be contradictory when they are compared with China, as higher CExC is obtained for lower fossil fuel contribution. This behavior is associated with the higher energy consumption factors per ton of fossil fuel considered in the whole fossil fuel value chain (extraction, processing and transport). For this study case, the energy consumptions factors (34,000 MJ_{ex}/t coal, 57,130 MJ_{ex}/t of oil and 1.27 MJ_{ex}/MJ natural gas) are higher concerning the factors used by Zhang et al. (2018) (29,000 MJ_{ex}/t of coal, 46,731 MJ_{ex}/t of oil, 0.96 MJ_{ex}/MJ natural gas). The significant differences are due to that reported in Zhang et al. (2018), which only considered the local fossil fuel extraction, excluding the transport stage. Accordingly, the large distances for fossil fuel transportation are the main reason for such a high index of CExC in the CES.

On the other hand, the system boundaries assumed for the accounting of the exergy life cycle could also bring differences in terms of CExC. In this sense, the lower cumulative exergy consumption reported by Brazil concerning China and the present case is because the indirect exergy consumptions related to the extraction, processing and transport stages were not being considered. As shown in Figure 2, the CES is strongly dependent on non-renewable energy sources. This performance is due to the high contributions of coal (39.6%) and natural gas (17.1%) on national electric generation (see Table 1). This consumption pattern makes the CES highly vulnerable to external fluctuations in energy markets. At the same time, the high dependency of fossil fuels could carry out a high carbon intensity for the Chilean energy sector mainly associated with low-efficiency steam power plants fueled with coal, in which efficiencies do not exceed 38% (based on LHV). In this sense, CES is the primary GHG contributor in Chile, representing 77.4% of total GHG emissions in 2013 (CNE, 2018). These results suggest the need for an electricity matrix less dependent on fossil fuels and low carbon. In correspondence, Chile had proposed the decarbonization plan of the energy sector, which consists in the gradual closure of 28 coal-fired power plants that are still operating in the country for 2040 (Government of Chile, 2015; Simsek et al., 2019). Studies reported by Lechón et al. (2018) corroborate that the decarbonization pathway by means of penetration of renewable technology is a feasible energy policy for reducing resources, such as fossil fuels, water and land, as well as carbon emissions. Therefore, a reduction of nearly 40% of CExC is expected for 2040.

Furthermore, the findings of this study suggest low intensity of water and land in the nexus (Figure 7). This performance is associated with the low quality of water and land in comparison with energy in terms of exergy. However, this does not mean that water and land do not play an essential role in the sustainability of electric systems at the regional and local scale. In this sense, the nexus dynamics are also correlated with climatic factors, environmental impacts, governance, and policies, as well as natural resource availability, which, at the same time, are very dependent on local socio-economic conditions.

Another critical issue that implies high CExC for non-renewable energy resources is related to resource consumption during their life cycle, which involves the extraction, processing, and transport. The significant contribution of the direct and indirect exergy consumption for coal could be justified by the high contribution of this fuel (39.6%) in the national electricity matrix, as well as the high energy demanded in extraction, processing, and transport stages (25.1 GJ/ton of coal).

In addition, coal extraction is also the reason for high indirect land uses, which represents 93% of total indirect land uses. Therefore, it can be concluded that fuel origin is relevant in the indirect exergy and land consumptions for consequences on overall exergy resources consumed during the whole fuel life cycle. These results are consistent with those reported by Lechón et al. (2018), who highlighted the relevance of land occupation for non-renewable technologies associated mainly for the fossil fuel extraction stages.

According to that, the natural gas, LNG and diesel also showed higher indirect exergy consumption than the direct exergy component. It means that higher resource volumes have been used to produce the fuel rather than itself exergy content itself. This behavior is related to the high energy consumption during the extraction and processing stages of each fuel, which represents above 94% of the total indirect energy inputs (GJex/MWh) of each one. The remaining indirect energy consumption (< 6%) is related to fuel transportation, which is negligible for all fuels.

The increment of renewable energy sources share (wind, solar, biomass, hydro) could reduce the CExC in CES, due to negligible indirect exergy demand. Nevertheless, the CExC values obtained here could be underestimated due to the exclusion of indirect resource consumption during the technology manufacturing stage, specifically for solar photovoltaic panels and wind turbines. In this sense, several studies highlighted the high primary exergy consumption during PV modules production (Kannan et al., 2006; Mahmud et al., 2018). Furthermore, the results reported also demonstrated that the manufacturing stage varies as a function of the material used in PV, implying variation from 22% to 81% of total exergy consumption (Gong and Wall, 2014; Kannan et al., 2006). In addition, the Life Cycle Assessment (LCA) of the battery solar-PV manufacturing also depicted significant impacts on water resources depletion, land use and natural resources (minerals) (Mahmud et al., 2018). The wind turbines are also characterized by high demand of natural resources (energy resources and material resources), as is demonstrated in most of the LCA impact methods (Chipindula et al., 2018; Davidsson et al., 2012). Haapala and Prempreeda (2014) found that the manufacturing stage for two 2 MW onshore wind turbines represented 78% of total environmental impacts during whole energy supply chains in the US. A similar environmental profile was reported by Chipindula et al. (Chipindula et al., 2018). The authors reported that the manufacturing stage contributes an average of 80% to total environmental impact, associated mainly with the material extraction/processing phase (72%). More recently, Lechón et al. (2018) highlighted the relevant extraction of raw materials(silicon mining) on land use impacts for wind and solar photovoltaic power. Therefore, higher CExC is expected for these technologies and, as a consequence, lower CDP.

According to the Chilean energy policy, a steep increment in the implementation of energy generation technologies, specifically those based on wind and solar sources, is expected for the near future (Doyle, 2016; Munguia, 2016). In consequence, lower CExC for CES could also be expected. Nevertheless, special attention should be paid to biomass because even when it is available in Chile as a promising resource, the value chain for its exploitation as an energy vector is intensively energy demanding. Indeed, the logistics associated with forest management and biomass transportation is one of the critical factors affecting the environmental profile of biomass-based technologies (Casas-Ledón et al., 2019; Morales et al., 2015). In the present analysis, the biomass value chain was not considered so that the indirect exergy consumption related to the energy component is underestimated. Therefore, the biomass value chain should be taken into account in further studies.

4.2. Water–Energy–Land Nexus Efficiency

The water–energy–land nexus efficiency was evaluated through the cumulative degree of perfection (CDP), which heavily depends on CExC and individual technology efficiency. Lower CExC and higher technology efficiency implies higher efficiency of water–energy–land nexus.

Technology efficiency plays an essential role in CDP. The technologies associated with non-renewable energy sources show a lower CDP (14%–19%) in comparison with renewable sources (13%–46%). The low CDP of non-renewable energy sources is related mainly to low efficiency, especially for coal-fired power plants (28% to 37%). The current power generation in Chile produces an average of 2.8 MWh per ton of coal in low-efficiency subcritical power plants in which efficiencies do not exceed 38% (based on LHV). Approximately 16% of existing coal-fired power plants have been in operation for more than 40 years; meanwhile, 76% have started-up in 2010 (CNE, 2018). The advanced supercritical and ultra-supercritical coal-fired power systems could be attractive alternatives for the improvement of efficiencies in coal-based power generation systems. These super and ultracritical technologies have efficiencies ranging between 42% and 44%, being higher than traditional subcritical power plants. Consequently, they should also reduce the GHG emissions of the Chilean electricity matrix. Nevertheless, the implementation of these alternatives has limitations because of the actual policy aiming to decarbonize the Chilean energy sector (Government of Chile, 2015; Mosquim et al., 2018).

On the other hand, the low exergy efficiencies found for non-renewable technologies (steam turbine, combined cycle, gas natural and internal combustion engines) are also associated with high indirect consumptions of exergy during the whole fossil fuel life cycle. As discussed previously, the indirect exergy inputs for fossil fuels have a significant (40%–80%) share in the total exergy consumption.

Furthermore, renewable sources technologies are dominated by hydropower plants, which represent 68.4% of total renewable electricity generation. The high exergy efficiency of hydroelectricity (46%) is due to the efficient uses of kinetic and potential exergy. These results are in concordance with Novak (2017) and Randriambahoaka, (2017). In contrast, solar photovoltaic (13%) and wind turbines (17%) are characterized by low CDP due to the low efficiency of wind and solar resource transformation into electricity (Bayrak et al., 2017; Ehyaei et al., 2019), which is strongly dependent on the technological parameters (wind speed, photovoltaic panel surface area and materials, direct solar radiation, etc.). One of the main inconveniences of non-conventional renewable energy resources is the intermittency problems (Dhakouani et al., 2019; Trainer, 2017), which could carry out the instability of the energetic supply.

Regarding energy resources (Figure 5a), the high contribution of energy into nexus is related to the high fossil fuel dependency of CES. This energy intensity (fossil fuels) of nexus could bring a threat to energy security due to its strong dependence on coal, oil and natural gas imports (Government of Chile, 2015; Vega-Coloma and Zaror, 2018). Furthermore, the presented results highlight the inverse proportionality between CDP (water, energy and land) and CExC.

In addition, the energy systems are vulnerable to global political, climatic and economic fluctuations. Moreover, climatic factors and environmental impacts associated with greenhouse gas emissions (GHG) also constitute an essential driver on water–energy–land interactions. In response, one of the goals of the Chilean Energy Policy is to achieve 60% renewable energy for electricity generation by 2050 (Ministerio de Energia, 2015). In this scenario, hydropower can play an important role. However, hydropower is highly vulnerable to climate change. In fact, Chile has registered a drastic reduction in rainfall, extensive drought and, consequently, water scarcity, which affects the plant factor for those technologies based on hydric resources (Arriagada et al., 2019). On the other hand, there is an intense competition between hydroelectricity generation with other water uses (i.e., irrigation, industry, domestic use, etc.). Furthermore, the superficial and underground water quality and availability have been affected by diffuse pollution , anthropogenic interventions and climatic changes (Díaz et al., 2018).

The low $CExC_{water}$ obtained for thermal power plants (coal) is interesting, but the water used for the cooling system is coming from the sea (approximately 76%), which is not accounted for in the nexus interactions. However, the combined cycles depicted significant differences in terms of water consumption concerning the rest of the technologies. This performance is due to the fuel type used in the combined cycles. In this case, the primary fossil fuel fed in this technology is LNG, representing 90% of the total of fuels. The relevance of LNG into the combined cycle carried out high freshwater demand, due to high specific water consumption per GJ of electricity generated (1.8 m^3/GJ for LNG).

From the land resources point of view, the main contribution is associated with land occupation related to renewable energy sources (solar, wind and biomass), except for some steam turbine power plants. The land-use intensity found for steam turbines can be justified by the high indirect land uses (98%) related to coal extraction, representing 91% of the total fuel feedstock to steam turbines.

Solar PV power plants are characterized by intensive land use. However, most of them are located in the northern region in the Atacama Desert, which is not in conflict with other land uses. Similar behavior is depicted for wind power plants, which are located along with the Chilean territory co-existing with other land uses (i.e., agriculture). In contrast, electricity coming from biomass power plants is land-intensive due to biomass extraction, but it was not considered here. In fact, forest management has led to an increase in land erosion (Banfield et al., 2018), causing a reduction of ecosystem services. At the same time, there has been found to be a negative impact on biodiversity (Heilmayr et al., 2016; Nahuelhual et al., 2012), habitat fragmentation (Echeverria et al., 2006), as well as a reduction of rivers basin’s morpho-sedimentary regulation capacity (Díaz et al., 2018). In general, the results presented here corroborated that nexus dynamics are heavily dependent on climatic factors, environmental impacts, governance, and policies, as well as natural resource availability, which at the same time are very dependent on local socio-economic conditions.

According to the previous discussion, the CES is intensive in terms of energy consumption, with an excessive (57%) dependence on fossil fuel importation, which could be a threat to energy security. However, the substitution of non-renewable energy sources by renewable ones could put pressure on water availability and land use at the local scale. The establishment of a common nexus typology in terms of metrics that could be used for evaluation at different scales is still a challenge. In this sense, the WELN evaluation should be focused on the quality of resources using the exergy concept. Specifically, the exergy concept allowed to unify the metrics associated with energy and water consumption, as well as land use. The exergetic indicator (CExC and CDP) used to evaluate the nexus demonstrated the relevance of indirect energy, water and land consumption due to the fossil fuel value chains.

Nevertheless, the nexus efficiency in terms of water and land resources were insignificant concerning energy resource. This performance demonstrated that the exergy concept visualized the energetic resources with the highest quality in comparison to water and land. The results could be confusing, considering that exergy analysis is a non-traditional tool for highlighting the water and land resources nexus. For the present study case, it is expected that energy resources will be more significant than water and land in CES. Nevertheless, the evaluation of WELN in other scales (forestry and agriculture sectors, basin, regions), where the land and water are intensively used, could provide major relevance of these resources with respect to the energy component. Accordingly, Silalertruksa and Gheewala (Silalertruksa and Gheewala, 2018) found the relevance of water and land resources in the evaluation of land–water–energy nexus with a focus on sugarcane production in Thailand.

On the other hand, several methods could be used for complementing and highlighting the water and land resources within WELN. In this sense, the water footprint (Silalertruksa and Gheewala, 2018) and environmental extended input–output analysis (Guan et al., 2019) could be used for the accounting of water resource interactions in different productive sectors. The water footprint has been widely used in the energy sector for accounting for the water demand following the life cycle thinking approach (Silalertruksa and Gheewala, 2018; Zhu et al., 2019). Besides, the environmental extended input–output analysis has been applied in the energy sector for the estimation of specific water consumptions associated with different technologies of electricity generation and fuel extractions (Guan et al., 2019; Kharak et al., 2013). This method is characterized by its flexibility for evaluating the nexus at different scales (e.g., productive process, economic sectors, basin, etc.), as well as the fact that the accounting is not only of the embodied water demand but also the land resources (Guan et al., 2019). From the land resource point of view, the ecological footprint could also be recommended (Charfeddine, 2017). The ecological footprint has been used to evaluate the impacts of the use of non-renewable energy (fossil fuels) on land impact, focused on soil quality (Akif and Sinha, 2020; Charfeddine, 2017). Considering the previous discussion, several methods could be used for highlighting the water and land resources. Nevertheless, those analyses are focused on each resource separately, limiting the comparison and integration with different processes and multi-scales. These aspects constitute the main challenges in the WEL nexus evaluation (Dai et al., 2018). Nevertheless, the novelty of single exergy-based indicators for the evaluation of the nexus would provide answers to the mentioned challenges.

Furthermore, relevant results were found when the analysis was focused on each resource separately. In this case, the renewable technologies depicted higher CDP, but higher land uses. In contrast, the non-renewable technologies were intensively water-dependent, remarking the indirect water consumption for the production of fossil fuel. Therefore, it can be concluded that the integration of LCA and exergy principles are suitable for evaluating the water–energy–land nexus efficiency through exergy-based indicators.

5. Conclusions

In an attempt to quantify the water–energy–land nexus using exergy-based indicators, this study determined the interaction between these resources in the Chilean Energy System (CES). The study constitutes the first approach for quantifying the water–energy–land nexus efficiency.

The results suggest that the WELN for CES is strongly dependent on energy resources but not of water and land resources. Furthermore, the indirect consumptions of exergy during the whole fossil fuel life cycle are significant for non-renewable technologies, implying the lowest exergy efficiencies (CDP).

In addition, the low water and land intensity of CES does not mean that these resources are irrelevant to the sustainability of the electric system at the regional and local scale. In this sense, several local problems had emerged as a result of unsustainable energy, water and land management.

The comparisons with similar studies are difficult to carry out due to a variety of metrics, conceptual frameworks and a different case of studies. Nevertheless, the integration of LCA and exergy principles could facilitate the comparison and integration with different processes. At the same time, it allows evaluating the water–energy–land nexus efficiency through a common exergy-based indicator, facilitating the decision-making towards the sustainability of using multiple energy carriers into territorial planning, as well as the integration between multi-scales (process, sectors, basin, countries).

On the basis of this paper, there are still unsolved questions regarding the exclusion of technology manufacturing in the system boundary, specifically for renewable energy sources. Therefore, the future work ought to be focused on considered this stage, as well as the electricity transmission in order to avoid the underestimation of exergy indicators.

2.3 Evaluación del Nexo Agua-Energía en el tratamiento urbano de agua potable en Chile, a través de indicadores exergéticos y ambientales

Enviado a Journal of Cleaner Production. Evaluation of the Water–Energy Nexus in the treatment of urban drinking water in Chile through exergy and environmental indicators (JCLEPRO-D-21-05010R2). Estado en revisión.

Abstract

This research assessed water–energy nexus (WEN) efficiency in Chile's drinking water treatment plants by integrating the life cycle concept and exergy analysis principles. The cumulative exergy consumption (CExC) attributed to freshwater and the energy required by drinking water facilities during the whole life cycle were determined. Water-related indicators, such as the water stress index (WSI) and blue water footprint (BWF), differentiated by region, were used to highlight the critical role of water resources within the nexus. The CExC depicted significant differences between regions (10–30 MJex/m^3), depending on the quality of raw water sources, pumping, and drinking water treatment (DWT) configurations. The WSI and the BWF varied spatially across the country due to climatic variability. Regions with a higher WSI (0.4–1) also implied higher CExC. This pattern can be justified by low water availability and poor water quality, which, at the same time, implied more energy-intensive technologies. Improving water and energy efficiency were identified as critical strategies for reducing the water and energy demand in the urban DWT systems.

Keywords: water–energy nexus; exergy analysis; urban drinking water treatment; water stress index; blue water footprint

1. Introduction

Nowadays, the global population growth, increasing urbanization, and socio-economic development standards have posed multidimensional challenges to the sustainable management of water, food, energy, and soils (Dilekli and Cazcarro, 2019). Specifically, water and energy are critical resources for socio-economic development; thus, they have been continuously under pressure owing to their decreasing availability and inefficient use (WEF, 2020; Yano et al., 2020). Furthermore, the strong interdependence between water and energy has originated a comprehensive framework defined as water-energy nexus (WEN). The WEN provides a better understanding of water and energy interactions by including a more integrative resource management approach (Ahmad et al., 2020).

The drinking water treatment (DWT) systems are excellent examples of the interdependencies established in the WEN framework. Many studies have evidenced the excessive energy consumed in the drinking water production from freshwater supplies (Chen et al., 2019; Lam et al., 2017; Warsinger et al., 2016). Analogously, water is crucial for energy. Water is used in the energy industry to produce fuels and electricity. In fact, in developing countries, 10% to 20% of withdrawals are used to meet industrial needs, including energy (WWDR, 2014). Accordantly, more energy is expected to be required to adapt water systems to meet increasing demand, regulatory requirements, and the effects of climate change (Lam et al., 2017).

As a consequence of the above-discussed, several studies have evaluated the DWT systems from a nexus perspective by integrating several metrics and methods (Bukhary et al., 2020; Moredia et al., 2017; Suárez and Urtubia, 2016). In this sense, Nault and Papa, (2015) developed a method that combines life cycle assessment (LCA) and economic input-output analysis to quantify the impacts of energy consumption in water distribution systems. Their results demonstrated that pumping accounted for more than 80% of the total energy consumption. Valek et al., (2017) arisen to similar conclusions as Nault and Papa, (2015), when they studied the urban water-energy-climate nexus in Mexico City. Similarly, Gude (2015) analyzed different alternatives increasing the energy efficiency of existing urban water systems, while Lam et al., (2017) quantified the energy use and intensity of water supply in 30 cities of Australia, Brazil, Canada, China, India, USA and Japan. They both found that the annual per capita energy consumption for water provision ranged from 10 to 372 kWh. These studies provide a clear message on the relevance of WEN in the DWT and its dependence on climate, topography, operational efficiency, and water use patterns. However, most researchers have focused on specific energy consumption, mathematical models, and environmental impacts. However, these studies ignored resources usage efficiency, and in many cases, the whole supply chain.

According to the latter aspect, exergy analysis (EA) could play an essential role in evaluating the resource efficiencies into WEN. It has become a consolidated method to evaluate the performance of several resource transformation processes by accounting for the inefficiencies caused by thermodynamic irreversibilities (Dewulf et al., 2007; Dincer and Rosen, 2013; Ifaei et al., 2019). In addition, the EA can be combined with LCA through cumulative exergy consumption (CExC), assessing resource consumption efficiency through a production chain (Selicati et al., 2021; Szargut, 2005). Recently, the exergy potentialities to evaluate the resource efficiency in the nexus framework have been demonstrated by Rodríguez-Merchán et al., (2019), who quantified the water-energy-land nexus efficiency (WELN) in the Chilean electric mix. These authors highlighted the potential of exergy metrics to evaluate the resource efficiency in the nexus using the CExC indicator and the indirect resource consumption (water, energy and land) during the whole electricity supply chain. However, the exergy concept did not provide enough information about the relevance of water to the nexus, due to the low exergy content of water concerning energy. In this sense, water footprint (WF) and water stress index (WSI) could complement the exergy analysis to account for the nexus impacts in water resources accurately.

The WF is a well-known multidimensional indicator of volumetric water use and pollution (D'Ambrosio et al., 2020; Hogeboom, 2020). On the other hand, WSI represents the relationship between total water use and water availability (Pfister and Bayer, 2014). Vanham (2016), highlighted that the water footprint (WF) concept may provide relevant information and data that allows to better represent and quantify the different water components (green, blue or grey) and their impact categories (food security, water security, ecosystem services, etc) into the water-food-energy-ecosystem nexus. In the same line, Gu et al., (2016), considers a footprint methodology to provide a path to understand the WEN of wastewater treatment plants in China. Liu et al., (2020) propose assessing the water-energy scarcity nexus risk in the trading system by combining WSI and WEN approaches. However, all these metrics are site-specific, limited to local regulations, quality and availability of water sources, and energy supply chains (technologies, fuels, etc); thus, they cannot be extended from one territory to another.

In the Chilean context, some efforts have been conducted to evaluate and provide evidence of nexus at different dimensions and case studies, such as water-food-energy nexus (Meza et al., 2015b) at the regional scale, water-energy-land (Rodríguez-Merchán., 2019) in the energy sector, and water-energy nexus for hydroelectricity (Kelly and Negroni, 2020) and medium-sized settlement (Vergara-Araya et al., 2020). Regarding WEN, Kelly and Negroni, (2020) discussed the WEN approach on how water, energy, and environmental institutions interact in Mapuche Indigenous territory, where small hydropower projects present conflicts. Moreover, Vergara-Araya et al. (2020) reported the environmental impact of implementing an integrated water, waste, and energy management system using the medium-sized settlement in Chile's central zone. This system integrated different resources and energy flow such as i) greywater and blackwater separation within the household, ii) Greywater is re-used after treatment, iii) blackwater and solid municipal waste are used to produce biogas, iv) the biogas is converted in a combined heat and power plant (CHP) into electricity and heat. The results depicted a feasible implementation of the integrated system due to its low resource consumption and environmental impacts.

Despite the efforts made to evaluate the WEN at the local scale, scarce studies address Chile's drinking water treatment systems. The only precedent found in the literature is the work reported by Suárez and Urtubia (2016), who developed a mathematical model involving technical variables of an integrated membrane distillation system with solar ponds based on site-specific solar irradiance and sea accessibility. Nevertheless, the authors restricted their nexus analysis for a specific drinking water technology and limited it to quantify the direct energy and water demanded.

As mentioned before, the nexus intensity could be diverse and complex, depending on geographical characteristics and socio-economic activities. Based on that, the WEN intensity in Chilean DWT systems could vary significantly along the country due to regional variability in water availability, quality, economic activities, and final consumers. Therefore, it is necessary to analyze the nexus by considering an integrated approach to quantify the technical implications of the DWT and their relationship with the resource availability and variability in the territory.

To the best of our knowledge, there are no studies in Chile that evaluated the WEN in the whole DWT systems combining the exergy analysis with water footprint and water stress index, which allow to assess the nexus efficiency and provide a better understanding of its dependencies with water availability and uses into the territory. Therefore, this study provides: i) the evaluation of the efficiency of water and energy uses in the Chilean DWT systems, using exergy metrics, ii) a comprehensive regional assessment of the water availability and uses, to demonstrate the critical role of water resources within the nexus, iii) systematic analysis of the interdependence between water and energy resources at regional levels and iv) a comprehensive discussion on the main factors that intensify the nexus, identifying potential opportunities that could contribute to implement feasible and more sustainable solutions for guarantying water and energy security at the national scale.

2. Materials and methods

2.1 Case study

Chile's DWT systems were selected as a case study, taking 2017 as the reference year. This case study focuses on urban systems (86.4% of total potable water). Rural systems were not considered due to a lack of information. The 99.9% of the Chilean urban population has access to potable water (Lillo et al., 2016). The drinking water quality must comply with the standard imposed in the drinking water regulations NCh 409/1 of 2005 (INN, 2005). The DWT process comprises the pumping and purification stages. In the pumping stage, 60% of the water extracted ($\sim 1.6\times10^{9}$ m^3/year) by drinking water plants was obtained from underground sources with depths greater than 100 m. The remaining 40% comes from surface sources close to the plants (<1 km). In the present study, approximately 400 water treatment plants were found to supply approximately 2x10^6 m^3/year of treated drinking water, covering 14 million people (Figure 10). Water demand was met by drinking water plants with the following technological combinations: (i) coagulation–flocculation with rapid gravity filters (13.5% of total plants); (ii) coagulation–flocculation with pressure filters (36%); (iii) disinfection with chlorination centers (CC) (46%); and (iv) reverse osmosis (4.5%) (Table 1). The data for the DWT in Table 4 and Figure 10 was obtained from SISS (2017). The privatization of the Chilean water industry involves a regulatory system managed by the SISS (Spanish acronym of "Superintendencia de Servicios Sanitarios"). The SISS is the urban Water Supply and Sanitation Regulator, within its attributions is to oversee the quality standards of drinking water and treated wastewater effluents.

The quality of the DWTs raw water throughout Chile is diverse in water availability and environmental chemistry (See Appendix Table A.2). Different natural and geological characteristics are observed from the northern to the southern regions, and there are also several production processes present in various catchment basins. In the northern regions, there is a higher concentration of dissolved salts, metals and metalloids. Further south, in central regions, the available water volumes increase, with a lower concentration of salts and metals. However, due to intensive agricultural activities and bigger urban areas, there is an increase in nutrients in surface water reservoirs, leading to eutrophic states, susceptible to algal blooms and the presence of taste and odor compounds and/or toxins. In the extreme southern regions, the water bodies are oligo or mesotrophic, with low concentrations of dissolved solids, except for the water bodies that receive effluents from the intensive fishing industry (Donoso et al., 2018).

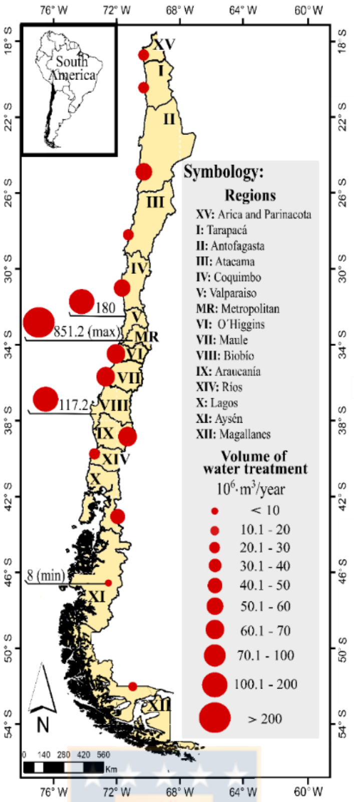

Figure 10. Chilean regions and treated drinking water volume by regions.

Table 4. Description of the Chilean urban drinking water treatment (DWT) system. The year 2017 (SISS, 2017).

Regions		**Number of plants per technology**					**Stocked population (10^3 habs/year)**	**Water treated (10^3 m^3/year)**	**(%)**
		RO	CF+RGF	CF+PF	CC	Others			
XV	Arica and Parinacota	3	-	3	-	-	196	20,401	1.3
I	Tarapacá	3	-	3	-	-	280	26,822	1.7
II	Antofagasta	3	5		-	-	532	54,736	3.4
III	Atacama	5	-	2	-	-	229	27,929	1.7
IV	Coquimbo	1	2	9	9	-	613	51,593	3.2
V	Valparaíso	2	9	13	27	-	1,670	179,834	11.1
MR	Metropolitana	1	20	10	49	-	6,657	851,289	52.6
VI	O´Higgins	-	2	7	27	1	614	61,326	3.8
VII	Maule	-	-	12	25	-	601	69,613	4.3
VIII	Biobío	-	9	29	26	-	1,196	117,224	7.3
IX	Araucanía	-	1	21	11	-	508	67,463	4.2
X	Lagos	-	4	9	1	-	455	47,159	2.9
XIV	Ríos	-	1	16	8	-	213	20,152	1.2
XI	Aysén	-	1	7	-	-	75	8,043	0.5
XII	Magallanes	-	-	3	-	-	149	12,448	0.8
	Total	18	54	144	183	1	13,988	1,616,032	100

RO: reverse osmosis; CF: coagulation–flocculation; RGF: rapid gravity filters; PF: pressure filters; CC: chlorination centers, Others: includes slow filters and ion exchange.

2.2 The evaluation of WEN in the DWT system

The LCA principles were integrated with the exergy concept to evaluate the WENs in the DWT system**.** The exergetic life cycle analysis (ELCA) was used to quantify the cumulative exergy consumption attributed to the freshwater and the energy during the whole life cycle of drinking water production.

2.2.1 Definition of system boundary and functional unit

The functional unit (Fu) selected was 1 m^3 of treated water. The treated water volume accounts for the total water used and the water losses associated with the final consumers and water distribution. The system boundaries for the supply chain of drinking water production were considered from the cradle-to-gate approach, including pumping and purification stages. The groundwater and surface water sources are considered in the water pumping stage; meanwhile, reverse osmosis, coagulation-flocculation, rapid gravity filters, pressure filters, and chlorination centers were the technologies studied in the water purification stage.

The water (W_D) and electricity (E_D) direct components are consumed directly by water pumping and purification stages. The indirect components are referred to as water (W_I) and energy (E_I) embodied during the life cycle of the Chilean Electric System (CES); specifically, the production chain of fossil fuels and electricity generation.

In this study, the infrastructure and construction of the DWT plants were excluded due to results reported by other studies, who have pointed the negligible resources consumption and environmental impact of the construction stage compared to the operation phase (Amores et al., 2013; Lemos et al., 2013; Santana et al., 2014). The energy and water resources consumed during chemical production (chlorine, aluminum sulfate, and polymer) required in the treatment plants were excluded because of low impacts on the resource demand category, according to Garfí et al. (2016) and Xue et al. (2019). The cradle-to-gate system limits for the urban DWT system are shown in Figure 11.

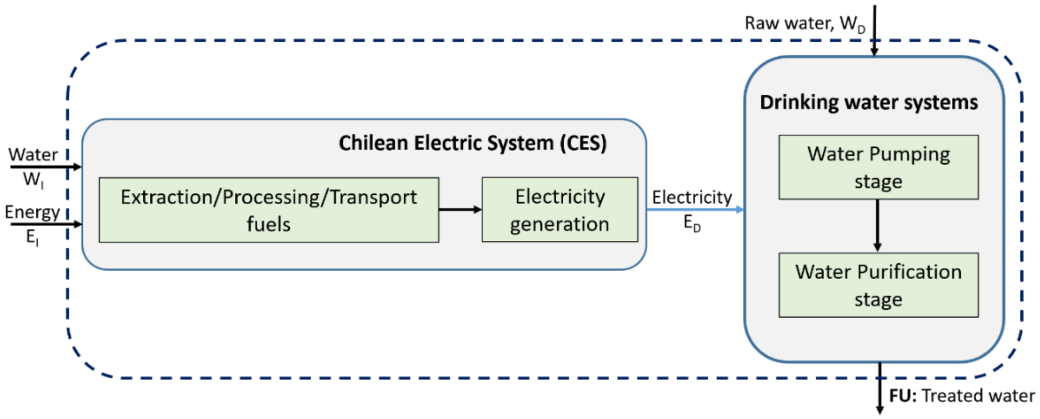

Figure 11. System boundaries for the urban DWT system in Chile.

2.2.2 Exergy evaluation

The evaluation of the WEN was based on the indicator of cumulative exergy consumption (CExC) approach (Szargut, 2005), which is defined as the sum of exergy of all resources required to provide a service or product. The CExC (MJex/m^3 of treated water) is defined as the sum of the exergy content of water and energy used in the supply of drinking water, considering the direct and indirect components. Therefore, higher CExC values represent higher water and energy consumptions; consequently, higher pressure over resources and low efficiency of water–energy nexus of the studied system. In this case study, CExC was evaluated according to Equation (1), taken from (Dincer and Rosen, 2013):

$$\mathrm{CExC}_{l,k} = \frac{\sum_{\mathrm{i,j}}\left(\mathrm{Ex}_{\mathrm{E}_{\mathrm{i,j}}} + \mathrm{Ex}_{\mathrm{W}_{\mathrm{i,j}}}\right)}{\mathrm{Fu}}, \qquad (1)$$

where Ex_E (MJex) and Ex_W (MJex) represents the exergy associated with the energy and water resources that enter the systems. The subscripts *i* and *j* refer to direct or indirect input resources, respectively. Finally, *l* and *k* refer to the type of pumping and purification technology.

The amount of water and energy required directly by water pumping and purification stages were counted in exergy (MJex). Exergy is defined as the maximum of work obtained from a system component relative to its reference environment. The reference state is assumed as the temperature of $T_o = 298.15$ K, pressure $P_o = 1.013$ bar, and the atmosphere composition specified by Szargut, (2005). The exergy of electricity consumed by systems is equal to the energy demanded by water pumping and purification stages (Szargut, 2005).

In this study, the water stream exergy was estimated considering only the chemical component (Equation (2)) because the potential, kinetic, and physical energy of the water resource was negligible concerning the reference environment (Szargut, 2005).

$$\mathrm{Ex}_{w} = \mathrm{Ex}_{\mathrm{w}}^{0} \times \mathrm{m}_{w}, \tag{2}$$

where Ex_{w} represents the chemical exergy contained in the water fluxes (MJex/year). The term $\mathrm{Ex}_{\mathrm{w}}^{0}$ is the standard chemical exergy of freshwater extracted from Szargut (2005) (5×10^{-8} MJex/m^3). m_{w} represents the volume (m^3/year) of pumped water that enters each purification plant.

2.3. Evaluation of WEN

Although the CExC evaluates the water–energy nexus in the same metric, it was of interest to complement this indicator with environmental indicators that describe local water resource dynamics. Thus, WSI and the BWF were selected to provide information about water availability, water use in a territory, and the dependence of consumptive-water uses for productive sectors. The BWF measures the volume of freshwater (m^3/s) extracted from surface and/or underground sources by different productive sectors and not returned to the environment (Hoekstra et al., 2011). In this study, the BWF values were extracted directly from FCH (2018) results and Jaramillo (2017), who had reported the specific BWF values for the different Chilean regions and economic activities. These BWF values were calculated as described in Hoekstra et al. (2011), which refers to consumptive use of surface and groundwater. It considers the water loss associated with water evaporation, not returned to the same catchment area and water incorporated into the product. More detail of specific parameters used for BWF estimations by each sector is available in Jaramillo (2017).

WSI was defined as the relationship between the water demand and water availability, and it was extracted directly from the monthly WSI map available in https://esd.ifu.ethz.ch/, which has been calculated based on the methodology developed by Pfister and Bayer (2014). The authors have developed the monthly WSI for more than 11,000 river basins globally, based on annual rainfall and water withdrawals reported by FAO for different countries, including Chile. The regional WSI values were obtained by the superposition of a satellite image of global WSI and Chilean administrative geographic division maps using ArcGIS 10.4 software. The WSI ranges values from 0.01 to 1, representing low water scarcity for values close to zero and maximum water scarcity for WSI equal to 1.

2.4. Data sources

The primary data related to urban DWT was taken from site-specific data, coming from 400 drinking water plants existing in the country and complemented with bibliographic sources.

For the DWT, the specific electricity consumption differentiated by each technology and water pumping system was not available. Consequently, the direct electricity required by the pumping stage and treatment technologies was complemented using the average factors reported by the literature. Specifically, for coagulacion-floculation, rapid gravity filtration, and pressure filtration processes, the electricity demanded was extracted from local studies (Molinos-Senante and Sala-Garrido, 2018, 2017); meanwhile, the specific energy consumption for the rest of the technologies was compiled from the literature (see Table 2).

Regarding electricity consumption factors associated with water pumping stages, the values from the literature were standardized per distance and depth for surface and groundwater sources, respectively. The treated water and demand by final consumers, the groundwater depth catchment, and the distance between the surface intakes and the plants were based on the operational characteristics of each DWT plant and were extracted from primary data available in the Environmental Impact Assessment System (SEIA, 2020).

The specific energy consumption factors by water pumping and treatment technology are summarized in Table 5.

Table 5. Electricity consumption factors by treatment technology and water pumping.

Technology	Average energy intensity (E_D) (kWh/m^3)	References
Rapid Mixing	0.02	(Hammer and Hammer, 2012; Plappally and Lienhard, 2012)
Coagulant and flocculation	0.03	(Molinos-Senante and Sala-Garrido, 2018a, 2017)
Sedimentation	7.5 x 10^{-4}	(Hammer and Hammer, 2012; Plappally and Lienhard, 2012)
Rapid gravity filtration	0.04	(Molinos-Senante and Sala-Garrido, 2018a, 2017)
Pressure filtration	0.21	(Molinos-Senante and Sala-Garrido, 2018a, 2017)
Slow filtration	6.8 x 10^{-4}	Plappally and Lienhard, 2012
Ion exchange	0.25	Plappally and Lienhard, 2012
Reverse osmosis (brackish water)	1.2	(Muñoz et al., 2010; OECD/IEA, 2016; Plappally and Lienhard, 2012)
Chlorine feeding	1 x 10^{-3}	Arpke and Hutzler, 2006
Pumping systems		
Surface water	0.005 kWh/m^3*km (distance)	(AG/DSEWPC, 2010; I Muñoz et al., 2010; OECD/IEA, 2016)
Groundwater	0.004 kWh/m3*m (depth)	(Cohen et al., 2004; OECD/IEA, 2016; US/GAO, 2012)

The embodied energy and water in the CES were gathered from Rodríguez-Merchán et (2019). The total exergy resources were 17.2 MJex per MWh of electricity for energy components, and 7.82×10^{-8} MJex/MWh was referred to as water resources. The summary of data sources used in WEN for urban DWT is presented in Table 6.

Table 6. Summary of data sources used for WEN

Data information	Data source
Treated water flows	(SEIA, 2020)
Groundwater depth	
Distance between the surface intakes and plants	
Water demand by final consumers	
BWF by Chilean regions and economic activities	(FCH, 2018; Jaramillo, 2017)
Spatial WSI values	https://esd.ifu.ethz.ch/
Embodied energy of CES, expressed in MJex/kWh	(Rodríguez-Merchan et al., 2019)
Embodied water of CES, expressed in MJex/kWh	

3. Results and discussion

3.1 Cumulative Exergy Consumption (CExC) in the nexus.

The total water and energy resources consumed for the Chilean DWT system expressed in exergy (CExC) are shown in Figure 12. Approximately 8.67 MJ_{ex} was required to treat 1 m^3 of water. The energy component represented 99.9% of the total CExC and the water contribution is negligible (0.1%) due to the low water exergy content concerning energy resources. This finding could lead to a misunderstanding about the relevance of water in the nexus. For this reason, several methods could be used to complement and highlight the water resources within the nexus. The water footprint (D'Ambrosio et al., 2020; Hoekstra et al., 2011) and water stress index (Pfister and Bayer, 2014) could be used to measure human appropriation of freshwater, water availability, and stress around the country. Both water-related indicators are discussed in Section 3.3.

Indirect energy represented 83% of total energy consumption and was higher than the direct component (17%). The direct energy was related to the electricity demanded by different treatment systems used. By comparison, the direct water flow accounted for most water resources and was responsible for 99.9% of the water supplied. The indirect water components related to the extraction, production, and transport stages of fossil fuels in electricity production were negligible (0.1%). However, the high non-renewable energy sources contribute to the Chilean electricity mix, and the energy consumption during the whole life cycle of fossil fuels was the leading cause of high indirect energy consumption in the nexus. Most of the electricity produced by the Chilean electricity matrix is generated using coal (39%) and natural gas (15%). According to Rodríguez-Merchán et al., (2019), 33% of CES's total cumulative exergy consumption was associated with the extraction, processing, and transport of imported fossil fuels.

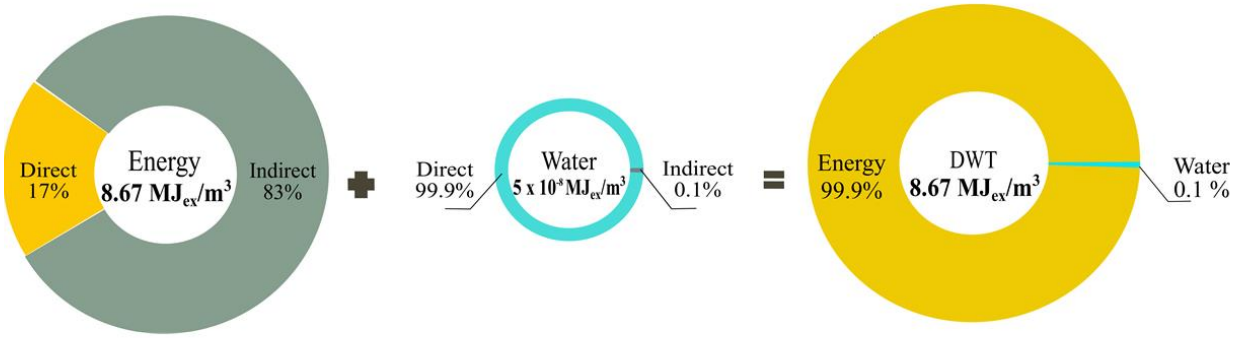

Figure 12. Demanded resources (cumulative exergy consumption, CExC) to treat drinking water in Chile by resource and flow.

These results are in concordance with Chen et al. (2014) and Seckin et al. (2012). In our case, the CExC for DWT in Chile was twice (8.67 MJex/m^3) of those obtained for similar systems reported in China (4.03 MJex/m^3) and Turkey (4.00 MJex/m^3). The significant differences were related to the direct electricity demand by water treatment and the indirect energy consumption associated with the fossil fuel life cycle involved in the electricity generation mix. The indirect exergy component consumption for the present case was 8% and 33% higher than China and Turkey's electricity mix, respectively. This pattern was also associated with stages considered boundary systems. Specifically, China and Turkey's energy mix was focused on local resources, excluding the exergy associated with fuel transportation. In contrast, most of the fossil fuels used in the Chilean energy mix are imported; consequently, transportation plays a critical role in the electricity generation mix (Rodriguez-Merchán et al., 2019).

3.2 Cumulative Exergy Consumption (CExC): geographical and technological dependence.

The CExC depicted notable differences between the north of Chile and the other regions, as shown in Figure 4. Northern regions XV, I, II, and III had values above 30 MJex/m^3 of treated drinking water. The rest of the regions depicted low CExC values below 10 MJex/m^3. The significant contribution of CExC for the northern regions is related to the high energy requirement for the DWT process, based on reverse osmosis (RO) technology (Figure 13). The high energy consumption associated with the groundwater catchment due to extensive aquifer depths (115–190 m) resulted in the higher CExC/m^3 of treated water for XV, I, and III regions.

The variety of technologies and the pumping operation processes implied disparities between the CExC values for each region. The pumping operation was determined as the highest energy consumer from IV to XIV regions, representing more than 60% of the total CExC in each region. Furthermore, the water treatment technologies are dominant in the final CExC for regions located in the extreme north (XV, I, II and III) and south (XI and XII) of Chile. The contribution of the treatment technology in the CExC for regions XI and XII is due to lower energy requirements for surface water pumping concerning rapid gravity and pressure filtration processes. Nevertheless, the relevance of pumping operations for regions located from IV to XIV can be justified by the higher energy demand for water catchment coming from groundwater sources compared to the conventional physical-chemical process (rapid gravity and pressure filtration processes). This energy consumption pattern is in concordance with Bukhary et al. (2019), who also found the most extensive energy requirements for pumping operations across the water supply chain.

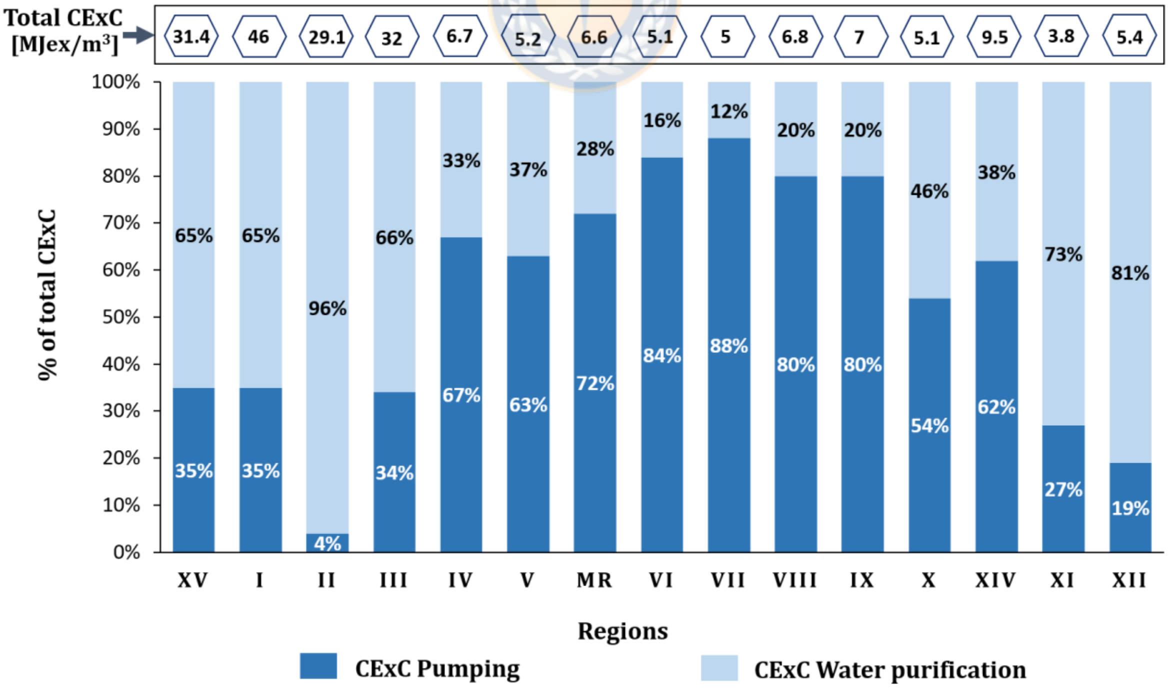

Figure 13. Contribution of the pumping and water purification stages in the total CExC by region.

As shown in Table 5, most water treatment comes from groundwater sources for all regions, except for II, XI, and XII regions, where more than 98% of water pumping is sourced from surface water. Furthermore, MR and XIV regions depicted significant surface water consumption, accounting for 57% and 75% of the total. In contrast, groundwater pumping is dominant for the north zones (XV, I, II, III regions) and VII region, representing above 93% of total treated water. Additionally, most of the regions located in the central-south zone (IV to XII and XV)) treated both natural water sources, with groundwater the primary source (61%–75%). However, surface water contributions are also significant for these regions, varying between 25% and 39%.

From the CExC point of view, groundwater pumping has still been relevant compared to surface water pumping, representing between 72% and 100% contributions. This pattern is strongly correlated to the high volume of groundwater pumping and the more energy-intensive groundwater pumping system concerning surface water pumping. The groundwater pumping (0.004 kWh/m^3 per meter of groundwater depth) system consumes 800 times more energy than surface water pumping (0.005 kWh/m^3 per meter of pumped surface water). In consequence, the high energy contributions for groundwater pumping were found for the MR (87%) and XIV (72%) regions, despite the higher water volume from surface water sources (57% and 75%).

This result is in concordance with Herrera-León et al. (2019) and Mannan et al. (2018), who concluded that the energy requirement for vertically pumping water at a depth of 100 m is equivalent to surface water transport at a distance of 100 km, and that the amount of energy required to supply surface water requires 20%–30% less direct energy than groundwater supplies. In this study, the groundwater aquifer depths varied between regions and fluctuated between 100 and 190 m, with region II having the greatest groundwater source depth (190 m). This behavior also contributed to the highest CExC (16.2 MJex/m^3) by water pumping found in Tarapacá.

Water availability constitutes a critical factor in defining the type of raw water withdrawal. In this case, the relevance of groundwater withdrawal in the south (from VIII to XII) regions, where the aquifers presented high water availability and good quality (DGA, 2020), could be contradictory. Thus, it is expected that higher DWT came from surface water instead of groundwater. This performance could be explained due to current water rights allocation and permitting, which vary significantly by region (Valdés-Pineda et al., 2014). Most water rights are requested for irrigation (35%–85%) and industrial practices (23%–60%). For domestic use, the water rights are below 15% of the water use distributed around the country. Therefore, surface water scarcity, competition with other water uses, and water regulation policies regarding surface water withdrawals could be factors that contribute to a higher percentage of groundwater uses.

Table 7. Contribution to CExC of the pumping stage and total water volume by type of water.

Region	**Water (m^3)**	**CExC pumping ($MJex/m^3$)**	**Contribution $CExC_{pumping}$ (%)**		**Contribution Total volume of water (%)**	
			Groundwater	**Surface water**	**Groundwater**	**Surface water**
XV	1.82×10^7	10.9	100		100	
I	2.68×10^7	16.2	100		100	
II	5.47×10^7	1.03	0.5	99.5	2	98
III	2.87×10^7	10.7	99.6	0.4	96	4
IV	5.16×10^7	4.5	99.5	0.5	98	2
V	1.80×10^8	3.2	88	12	63	37
MR	8.51×10^8	4.8	87	13	43	57
VI	6.16×10^7	4.4	94	6	75	25
VII	6.94×10^7	5.3	99	1	93	7
VIII	1.17×10^7	4.8	92	8	61	39
IX	5.83×10^7	6.1	95	5	69	31
X	4.72×10^7	2.8	72	28	69	31
XIV	1.99×10^7	6	95	5	25	75
XI	6.40×10^6	1.05	2	98	1	99
XII	1.25×10^7	1.04		100		100

Regarding water facilities (Figure 14), the primary technologies used were RO, coagulation-flocculation coupled with rapid gravity filtration and pressure filtration (See Table 1). As mentioned previously, the north of Chile is characterized by using RO; meanwhile, there is a combination of various processes for the central-south zones, being the rapid gravity and pressure filtration the technologies with higher relevance. However, the pressure filtration process is adopted by VII, IX, X, and XII regions (see Appendix Table A.1).

The differences in DWT found in Chile correspond to the quality of raw water sources available in each region. Arsenic is the primary pollutant for the upper north zone independent of raw water sources (groundwater and surface water), and in some cases up to twice the national water standard (Valdés-Pineda et al., 2014). By comparison, the high concentrations of salts are the primary pollutant issues in the northern regions, particularly sulfates, manganese, and chloride due to geological formations (DGA, 2020) (see Appendix Table A.2). Consequently, reverse osmosis is the most feasible technology to remove these pollutants to comply with national water standards reached.

On the contrary, the central-southern regions present better raw water quality, and turbidity and iron are the major quality issues (DGA, 2020). Therefore, the integration of coagulation-flocculation with pressure filters (40%–90%) and rapid gravity filters (25%–58%), and slow filters (1%–23%) (Figure 14), is more common for the removal of turbidity and iron, which are less energy demanding than reverse osmosis.

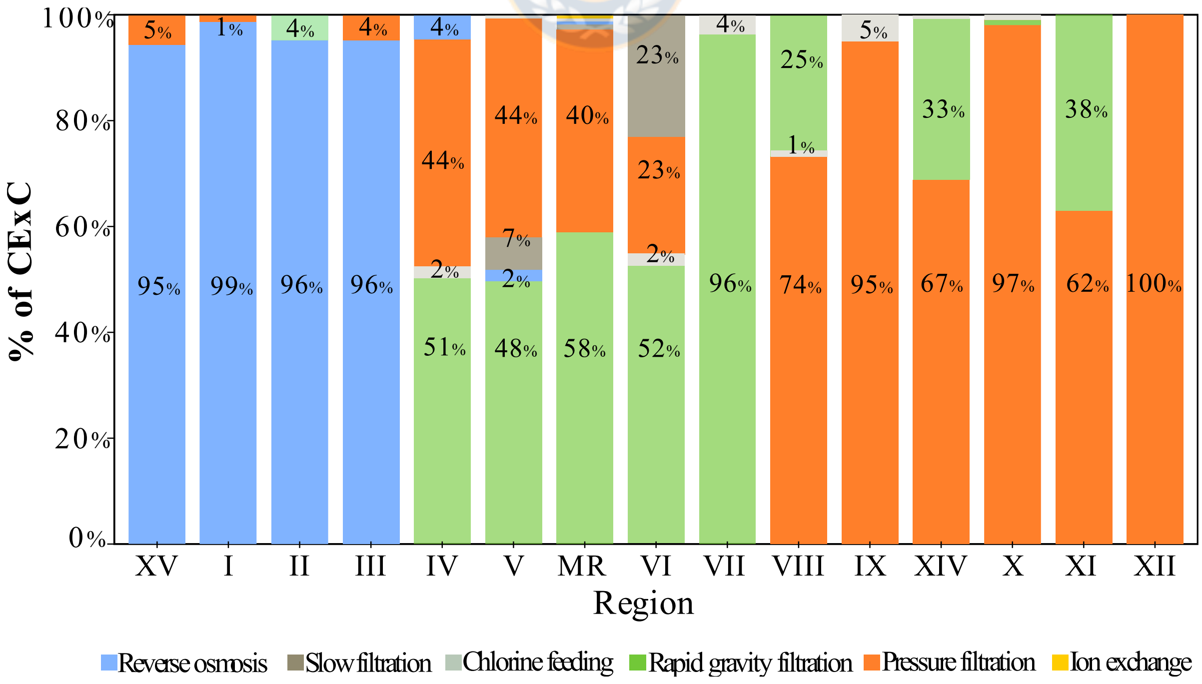

Figure 14. Contribution of cumulative exergy consumption (CExC) by technologies.

According to our findings, the Chilean DWT system is intensive in exergy consumption, mainly related to the high electricity consumption of natural water pumping and purification stages. The high electricity demand response to the energy-intensive process is used to treat one cubic meter of raw water, specifically reverse osmosis. This pattern carried out the relevance of the indirect exergy component (83%) due to the contribution of the fossil fuel value chains involved in the Chilean electric mix. The integration of existing DWT with local renewable energy sources, such as solar photovoltaic (PV), could reduce the energy requirement from the national system and, consequently, the indirect energy from fossil fuel generation, as well as the environmental impact associated with the energy-fossil fuel generation (Alvez et al., 2020). Simultaneously, the energy supply system could generate renewable energy for multiple local purposes. In this sense, some studies have evaluated photovoltaic integration with potable water treatment (Bukhary et al., 2020, 2019), demonstrating its feasibility from economic and environmental (carbon emission) criteria.

Furthermore, Chile has a vast solar energy potential located mainly in the northern zones, which gives an enormous opportunity for renewable energy integration with potable water treatment systems (Alvez et al., 2020; Munguia, 2016). However, environmental impacts on biodiversity, natural resource depletion, land-use change, soil, water resources, and human health could emerge throughout the lifetime of utility-scale solar systems (Mahmud et al., 2018; Rabaia et al., 2021). Regarding water resources impacts at the local scale, solar technologies may require water for cleaning (solar collectors and concentrators) and cooling systems, which could vary significantly in the function of solar technology (CSP or PV), type of cooling system (wet, dry and hybrid), system specifications (orientations, tilt angle and glazing properties) and the local climatic conditions (soil/dust properties, air pollution and rainfall rates, wind directions and speeds, relative humidity, and seasonal). For instance, the wet cooling (3100-3800 L/MWh) used for CSP is the most water-intensive technology compared to hybrid (600-1300 L/MWh) and dry cooling systems (100-400 L/MWh). Meanwhile, PV requires significantly less water consumption (20-150 L/MWh), mainly associated with cleaning systems (Ali and Kumar, 2017; Rabaia et al., 2021). Therefore, the CSP technology in the northern zone would imply more pressure on water resources in the nexus due to high water demand. The low water consumption suggests that PV could be the most feasible alternatives for those regions that already register a severe water deficit.

Another environmental aspect that should be considered is the large surface area required by solar technologies, which could intensify the conflict between land uses and landscape impacts. In this sense, concentrated solar systems (media=9.7 ± 0.4 W/m^2) has the higher power density concerning utility-scale (media= 5.8 ± 1.2 W/m^2) and residential PV (media= 6.7 ± 0.9 W/m^2) (van Zalk and Behrens, 2018). Implementing any solar technology in the northern region of Chile, specifically in the Atacama Desert, could be an attractive solution because there is no conflict with other land uses. Nevertheless, different scenarios could emerge for the rest of the country due to differences in land uses.

3.3. Water-related environmental indicators

The water stress index (WSI) and blue water footprint (BWF) indicators were used to highlight the water resource in the nexus. As shown in Figure 6, the WSI gradually increased from the south (0.1) to north (1.0) zones, according to unequal spatial distributions of water availability in the country, precipitation variability, groundwater storage, and glacial meltwater (Alvez et al., 2020). The central regions of Chile (V to VII)) showed a significant water deficit (varying from 0.4 to 0.6), despite the moderate annual rainfalls (Lillo et al., 2016).

By comparison, some southern regions may experience a progressive increment of water stress, but this may not be reflected as water scarcity. Regions with significant water stock (low WSI), but characterized by low-quality water could suffer water stress (Nepomilueva, 2017). For instance, the Biobío basin located in the south of Chile is characterized by a very high self-purifying capacity. However, its water quality has experienced a deterioration in the basin's lower section due to agricultural and industrial activities (Parra et al., 2013). Similar experiences have been reported for other surface water sources (Cachapoal river basin located in VI region, Ñuble river in XVI region, Rupanco Lake located in X region), where the pesticides and fertilizers resulting from agriculture practices are the main pollutants (Climent et al., 2019; León-Muñoz et al., 2013; Montory et al., 2017). Therefore, water stress for these regions due to water pollution is expected, incrementing the conflict and competition between water users.

Water availability could also affect the energy from hydropower plants (Zhang et al., 2018). Currently, hydroelectricity contributes to the Chilean energy mix, representing 29% of total electricity generated (Rodriguez-Merchán et al., 2019). However, this contribution could be reduced due to water availability and variability caused by climate change, leading to higher fossil fuel contributions. Arriagada et al. (2019) found a potential reduction of 22 to 47 MW/year of hydropower potential during 1970–2016 for four Chilean basins (Maipo, Maule, Biobío, and Bueno), due to streamflow regime alteration reduction. In this scenario, the DWT system could increment the indirect component of CExC if the energy deficit is supplied by fossil fuel. This discussion demonstrates the heavy interdependence between water and energy resources, and the strong dependence on climate change, allowing a comprehensive understanding of water availability interaction with energy generation and the energy uses for water supply. Simultaneously, these results suggest the need to consider climate change adaptation strategies in water and energy planning to guarantee future supply security (Bonelli et al., 2014).

In addition to natural factors derived from climate change, the exponential growth in water needs to meet agriculture, mining, energy generation, and residential demands, coupled with water quality deterioration due to diffuse pollution, are additional aspects that exacerbate water scarcity (Valdés-Pineda et al., 2014). As shown in Figure 15, the higher blue water footprint (BWF) values are located in the central regions. The VII region accounted for the highest water demand (50.1 m^3/s), followed by VI (44.1 m^3/s), MR (36.1 m^3/s), and V (25.9 m^3/s). The IV and VIII regions also depicted a significant BWF, with 22 and 12.4 m^3/s, respectively. Meanwhile, a lower BWF was obtained for the far north and far south regions, which varied between 0.2 and 5.7 m^3/s. The high water demand for central zones is mainly associated with the agriculture sector's high water requirement, demanding by each region approximately 68%–94%. It is essential to highlight that agriculture practices imply high water demand and could significantly deteriorate the surface water quality due to agrochemicals, implying more stress on water resources (Climent et al., 2019; Montory et al., 2017). In consequence, more energy-intensive technologies could be required for drinking water treatment, thus implying higher CExC.

The improvement of water use efficiency constitutes the critical factor for water management sustainability and should be adopted as common practice for all sectors. Thus, there are several opportunities to improve water efficiency in DWT systems, specifically at the final user level. For instance, the re-use of greywater from the household wastewater (e.g., toilet flushing, water infiltration, or soil irrigation of non-edible plants) could be an interesting water reduction strategy for the domestic sector. Indeed, successful greywater re-use experiences have been implemented in many countries such as United States, Japan, Australia, Germany, and California (Roshan and Kumar, 2020; Vuppaladadiyam et al., 2019). The re-use of greywater could significantly reduce urban water supply, contributing to reduce the pressure and stress on local freshwater resources, with approximately 50–80% of households' total wastewater to potentially be able to recover (Vergara-Araya et al., 2020). However, the main barrier is public acceptance (Amaris et al., 2020).

In addition, seawater desalination by reverse osmosis integrated with solar energy sources could be an opportunity to reduce the increasing shortage of freshwater, particularly for the north and central regions, which have experienced a severe water deficit (Alvez et al., 2020; Garg and Joshi, 2014), and present a high solar energy potential (Garg and Joshi, 2014; Suárez and Urtubia, 2016). Several authors have studied the technical and economic feasibility of integrating solar power and desalination plants for drinking water treatment systems in the Chilean context. In this sense, Mata-Torres et al. (2017) and Valenzuela et al. (2017) found the competitive values of Levelized drinking water treatment costs, which varied between 0.68-2.2 USD/m^3 for different configurations of concentrating solar power (parabolic trough collector, poly generation system, photovoltaic (PV) system) and desalination technologies (multi-effect distillation (MED) plant). However, small-scale decentralized desalination water treatment systems have shown to be more costly, oscillating between 1.6 and 33 USD/m^3 (Ahmadi et al., 2020). Despite the feasibility of the renewable desalination systems from a technical and economic perspective, several challenges still exist during the implementation of both technologies. In this sense, harmful algal bloom events, the disposal of desalination concentrate, and the high energy consumption by water supply systems were identified as the main challenges for desalination systems in Chile (Herrera-León et al., 2019). Solar energy constitutes a promising alternative to replace fossil fuel-based energy water treatment plants; however, special attention should be taken to environmental impacts throughout the life cycle (Mahmud et al., 2018; Rabaia et al., 2021).

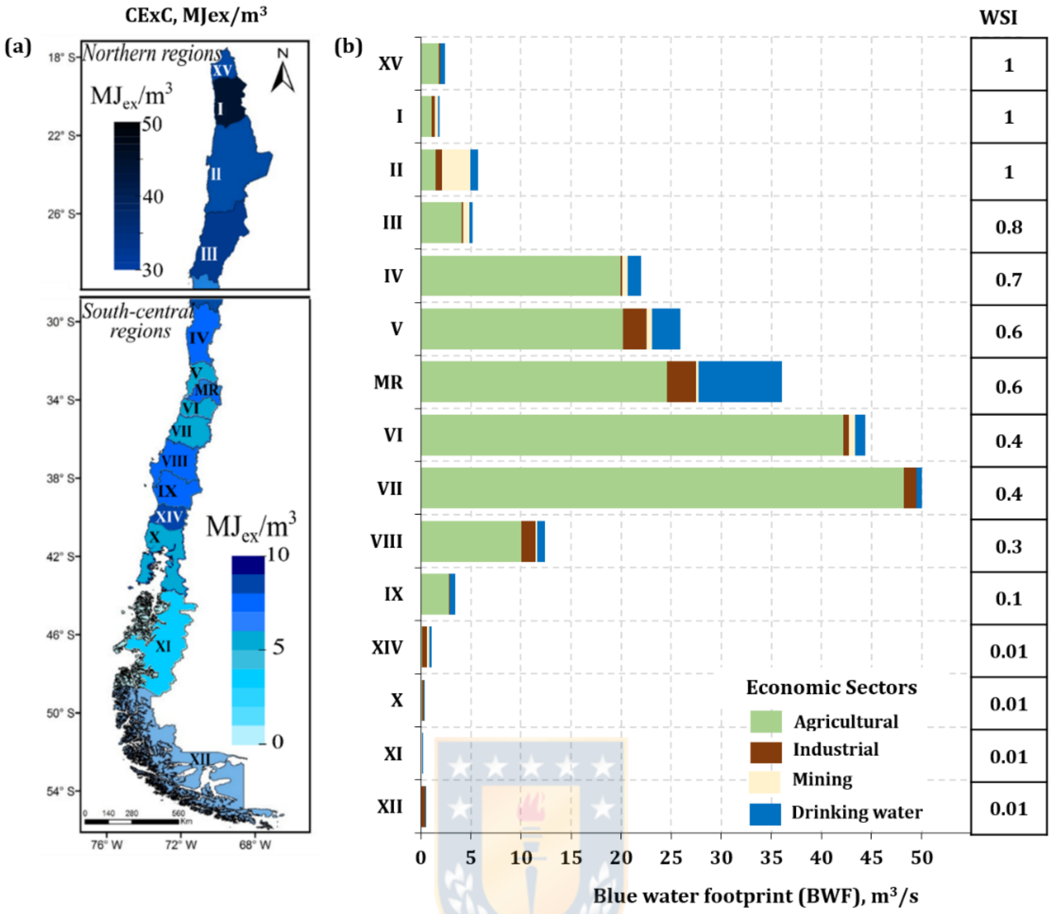

Figure 15. Exergy and water-related indicators dependence by region. **(a)** Cumulative exergy consumption (CExC) and **(b)** Blue water footprint by economic sectors and WSI by regions.

Furthermore, the CExC for DWT depicted a certain correlation with the WSI. This indicates that regions with higher WSI also implied a higher CExC, particularly for the northern regions (Arica and Parinacota, Tarapacá, Antofagasta, and Atacama). This pattern can be justified by low water availability and poor raw water quality, which at the same time implied more energy-intensive technologies (reverse osmosis). Nevertheless, this correlation was not clear for the remainder of the regions, even though the water sources' availability and quality are enhanced around the country, and the water facilities have low energy demand. Several factors could cause the non-linear water-energy nexus patterns, such as climatic variability, water availability and quality, differences in water purposes and demand, economic structures, technology levels (water and energy efficiency), and policy-related resources management (Rodriguez-Merchán et al., 2019).

4. Final remarks

Several aspects should be improved in the WEN of Chilean urban DWT. In this study was demonstrated that energy consumption is a crucial parameter in drinking water treatments. Therefore, energy efficiency improvement is required to reduce the energy demand and the CExC per cubic meter of treated water. Several factors could impact the energy demand for each water facilitiy such as water treatment capacity, water treatment plant ages, the economy of scale, raw water quality, and the pollutant removal efficiency (Molinos-Senante and Sala-Garrido, 2018, 2017). In this study, the specific energy consumption factors were assumed constant by type of technology (see Table 3) and water pumping system without considering the influence of those factors on CExC due to a lack and completeness of the information. Therefore, the CExC values present uncertainties associated with the completeness and precision of the technical data. For more efficient energy management of the drinking water treatment system, the uncertainty analysis involving each technology (plant capacity and age, pollutant removal) should be considered. The sensitivity analysis is recommended by ISO standards 14040/44, 2006, and it constitutes a well-established approach and the most common practice in traditional uncertainty quantification for LCA scenarios, which can help gain more insight into the robustness of the results.

Besides, several studies have pointed the relevance of resource consumption and environmental impact of water distribution networks during the operation stage compared to other phases into urban water cycle systems. In this sense, Amores et al. (2013) and Lemos et al. (2013) reported that the contribution of water distribution networks during the operational stage on energy resources categories could vary approximately 26-28%, being significant compared to water abstraction and treatment (32-42%) and wastewater treatment (29-34%). This performance is justified by high electricity consumption. Therefore, the CExC values obtained here could be underestimated due to the exclusion of the distribution stage. Accardantly, higher CExC is expected for the DWT if the water distribution is included in the boundary system. The water distribution relevance could change depending on local conditions such as distances and topography, pumping efficiency, and local energy matrix characteristics. Based on that findings, we suggest extending the DWT system boundaries up to the water distribution networks.

The exergy and environmental analysis results highlighted the complexity WEN and its dependence on local conditions. Nevertheless, the studied indicators could not be easily understood by decision-makers due to different dimensions. This problem could be solved by applying multi-criteria decision analysis (MCDA), which supports complex decision-making situations with multiple and often conflicting objectives. In this context, Lee et al., (2018) had applied the multi-criteria decision-making for sustainable water resource management in the WEN, considering economic and environmental criteria. The authors demonstrated that economic feasibility was considered the most crucial factor in implementing the practices; meanwhile, groundwater pumping control and management was ranked as high-priority water resource management actions. Other authors have also applied the MCDA in the nexus framework (Komendantova et al., 2020; Psomas et al., 2018). Therefore, is recommended to expand the present study with an MCDA approach, which could support the decision-makers to establish sustainable water-energy nexus strategies in urban DWT.

5. Conclusion

In an attempt to understand the complex interdependence of water and energy resources at local levels, this study evaluated the water-energy nexus in the Chilean urban drinking water treatment system, integrating the exergetic and local water-related indicators (WSI and BWF).

The results emphasized the strong dependence of the energy resources into the nexus, mainly associated with indirect exergy consumption during the life cycle of fossil fuels involved in the Chilean energy matrix, representing 83%. This result implied a significant contribution of CExC in the DWT. The greater CExC was registered in the northern zones (30-50 MJex/m^3) than central-south regions (1-10 MJex/m^3), due to more energy-intensive technologies (reverse osmosis) used for the treatment of lower quality raw water. The reduction of CExC along the country (from north to south) indicates improved raw water quality, implying fewer energy-intensive technologies for water treatment.

Furthermore, the WSI was gradually increased from far south to north zones, registering the highest water stress index (0.5–1) for north-central zones. The results emphasize that WSI could suffer a drastic reduction for central- north regions and some areas of the southern regions due to climatic changes and additional pressure by water consumers (demand and pollution). Accordantly, the higher BWF (26-50 m^3/s) was located in the central regions compared to the rest of the country (1-15 m^3/s).

The highest WSI and CExC values demonstrated that the water-energy nexus was stronger for the northern zone of Chile than the rest of the regions, which could intensify progressively towards the central zone due to high BWF coupled with effect to climatic changes. Therefore, the improvement of water and energy uses efficiency was identified as the critical factors to reduce the pressure of WEN in the urban DWT, and climate change adaptation strategies should be taken into account for more sustainable water and energy management.

According to our findings, uncertainty analysis is required to gain more insight into the robustness of the results, mainly associated with the completeness and precision of the technical data. Moreover, the exclusion of water distribution networks in the system boundary could imply underestimating exergy indicators; therefore, future work should include this stage. Finally, future studies should also be addressed the multi-criteria analysis to solve the multi-dimension factors in the nexus, providing a better water-energy nexus understanding and facilitating the decision-making towards optimal strategies for more sustainable WEN in urban DWT.

Appendices A

Table A.1. Contribution to CExC of purification stage by type of technology.

Regions	**Total volume of water (m^3)**	**CExC Purification ($MJex/m^3$)**	**Reverse Osmosis**		**Rapid gravity filtration (RGF)**		**CF + RGF**		**Pressure filtration (PF)**		**CF + PF**		**Slow filtration**		**Ion exchanges**		**Chlorine feeding**	
			% water	**% CExC**	**% water**	**% CExC**	**% water**	**% CExC**	**% water**	**% CExC**	**% water**	**% CExC**	**% water**	**% CExC**	**% water**	**% CExC**	**% water**	**% CExC**
XV	1.82×10^7	20.5	78	95.3					22	4.7								
I	2.68×10^7	30	97	98.6							3	1.4						
II	5.47×10^7	28.1	37	96.1			63	3.9										
III	2.87×10^7	21.3	80	95							20	5						
IV	5.16×10^7	2.2	0.4	4.7	0.6	0.5	64	50	22	44.6							13	0.2
V	1.80×10^8	2	1	7.2	14	11.4	43	35.2	11.5	27.8	6	14.5	4.5	3.5			20	0.4
MR	8.51×10^8	1.8	0.04	0.6			63	58.2			14	39.5	2	0.8	0.03	0.4	21	0.4
VI	6.16×10^7	0.7					25	52.2	0.1	0.7	2.9	21.8	23	23			49	2.3
VII	6.94×10^7	0.8									13	95.8					87	4.2
VIII	1.17×10^8	2			2	1.2	30	25	11	26.2	19	47					38	0.6
IX	5.83×10^7	1					6	1.2	26	88	3	9					65	1.8
X	4.72×10^7	3.5			1	0.1			83	99.7							16	0.2
XIV	1.99×10^7	2.3			32	32.6			36	67.3							32	0.1
XI	6.40×10^6	2.8					61	38	39	62								
XII	1.25×10^7	4.4							100	100								

CF: refers to the process of coagulation and flocculation

Table A.2. Range of water quality parameter mean values by regions. Extracted from (DGA, 2020)

Regions	**Type of water**	**pH**	**EC (µs/cm)**	**DO (mg/L)**	**Macroelements (mg/L)**				**Metals totals (µg/L)**						**COD (mg/L)**
					Cl$^-$	**N**	**HCO$_3^-$**	**SO4^{2-}**	**As**	**Cr**	**Cd**	**Cu**	**Fe**	**Mn**	
XV	SW	<6 - 9	0 - 5.7 x 10^4	5 - 14	0,5 – 1,9 x 10^4	0.005 - 4	5 - 589	0.4 - 2,690	10 - 2000	4 - 67	2 - 87	1 – 2,000	10 – 7.6x10^5	1 - 1.4 x10^4	0.5 - 60
	GW	NR	NR	5 - 9	NR	NR	NR	NR	NR	NR	7 - 10	NR	NR	1 - 100	8 - 20
I	SW	7 - 9	0 - 5.7 x 10^4	5 - 14	0,5 – 1,9 x 10^4	0.005 - 1	5 - 589	0.4 - 2690	0,5- 1.4x10^4	10 - 50	2 - 7	8 – 2,000	10 -5,000	1 - 2,000	8 - 168
	GW	7 - 9	751 - 1.1 x10^4	1 - 9	100 - 2,700	0.03 - 1	5 - 275	0.4 – 500	0.5 - 1,000		7 - 10	8 - 20	300-2.4x10^4	1 - 4,000	8 - 20
II	SW	7 - 9	0 - 5.7 x 10^4	5 - 9	0,5 – 1,9 x 10^4	0.005 - 1	80 - 589	0.4 - 1,000	10- 1.4x10^4	7 - 50	2 - 7	8 -2,000	10 – 5,000	1 - 2,000	8-60
	GW	7 - 8	751 - 1,500	1 - 9	400 - 2,700	0.03 - 1	80 - 160	0.4 - 250	10 - 1,000	10 - 50	7 - 10	8 - 20	10 - 300	1 - 100	8 - 20
III	SW	7 - 9	0 - 5.7 x 10^4	5 - 14	0,5 – 1,9 x 10^4	0.005 - 11	5 - 589	0.4 - 2,690	0.5 - 2,000	4 - 50	2 - 7	1 -2,000	10 - 5,000	1 - 2,000	0.5 - 60
	GW	7 - 8	751 - 1,500	1 - 9	100 - 200	0.03 - 11	80 - 275	0.4 - 500	0.5 - 1000	10 - 50	7 - 10	1 - 8	10 – 2.4x10^4		8 - 72
IV	SW	<6 - 9	0 - 5.7 x 10^4	<1 - 14	0,5 – 1,9 x 10^4	0.005 -11	5 - 589	0.4 - 1,000	0.5- 1.4x10^4	4 - 50	2 - 30	8 - 3.6x10^4	10 -7.6x10^5	1- 1.4 x10^4	8 - 60
	GW	7 - 8	0 -1,500	1 - 9	0.5 - 100	0.03 - 4	5 - 275	0.4 - 250	0.5 - 10	4 - 50	7 - 10	8 - 20	10 - 5,000	1 – 2,000	0.5 - 20
V	SW	7 - 9	0 - 5.7 x 10^4	<1 -14	0,5 – 1,9 x 10^4	0.005 - 11	5 - 275	0.4 - 2690	0.5 - 1,000	4 - 50	2 -7	1 - 3.6x10^4	10 - 5,000	1 - 2,000	8 - 60
	GW	7 - 8	751 - 3,000	1 - 9	400 - 2,700	0,03 - 4	80 - 160	250 - 500	0.5 - 10	7 - 50	7 - 10	1 - 20		1 - 100	
MR	SW	<6 - 9	0 - 3,000	5 - 14	0.5 - 400	0.005 - 11	5 - 275	0.4 - 2690	0.5 - 1,000	7 - 50	2 -7	1 - 3.6x10^4	10 - 7.6x10^5	1 - 2,000	0.5 - 168
	GW	7 - 8	0 - 1,500	5 - 9		0.03 - 21	160 - 275	0.4 - 500			2 - 10	1 - 20	10 - 5000	1 - 100	8 - 20
VI	SW	7 - 9	0 - 750	5 - 14	0.5 - 100	0.005 - 4	5 - 160	0.4 - 250	0.5 - 1,000	10 - 50	2 - 7	1 - 3.6x10^4	10 - 5,000	1 - 2,000	0.5 - 60
	GW		0 - 3,000	1 - 9	0.5 - 200	0.03 - 11	80 - 275			7 - 50	7 - 10	1 - 20			0.5 - 20
VII	SW	7 - 8	0 - 1,500	5-14	0.5 - 100	0.005 - 4	5 - 589	0.4 - 250	0.5 - 1,000	10 - 50	2 -7	0.8 – 2,000	10 - 5,000	1 - 100	8 - 60
	GW		0 - 750	1 - 9	0.5 - 200	0,03 - 4	160 - 464		0.5 - 10		7 - 10	1- 20		1 - 4,000	0.5 - 20
VIII	SW	7 - 9	0 - 750	5 - 14	0.5 - 100	0.005 - 4	5 - 80	0.4 - 250	0.5 - 1000	10 - 50	2 -7	1 - 2000	10 - 5,000	1 - 2,000	0.5 - 60
	GW			1 - 9		0.03 - 4	5 - 80			7 - 50	7 - 10	1 - 20	10 - 300	1 - 100	8 - 60
IX	SW	7 - 9	0 - 750	5 - 14	0.5 - 100	0.005 - 1	5 - 80	0.4 - 250	0.5 - 10	10 - 50	2-7	1 - 20	10 - 5,000	1 - 100	0.5 - 20
X	SW	7 - 8	0 - 750	5 - 14	0.5 - 100	0.005 - 1	5 - 80	0.4 - 250	0.5 - 10	10 - 50	2 - 7	1 - 20	10 - 5,000	1 - 100	0.5 - 60
	GW	7 - 8		1 - 9	NR	0.03 - 1	5 - 80				7 - 10	1 – 2,000		1 -2,000	0.5 - 20

XIV	SW	7 - 8	0 - 750	5 - 14	0.5 - 400	0.005 - 1	5 - 80	0.4 - 250	0.5 - 10	10 - 50	2 - 7	1 - 20	10 - 5,000	1 - 100	0.5 - 20
XI	SW	7 - 8		10-14	0.5 - 100		5 - 80					1 - 2,000			
XII	SW	7 - 9			0.5 - 200		5 - 275			7 - 50		1 - 20		1 - 2,000	0.5 - 60

SW: surface water; **GW:** groundwater; **EC (µs/cm):** electric conductivity; **DO:** dissolved oxygen; **Cl^-**: chloride; **N**: nitrogen; **HCO_3^-**: bicarbonate; **$SO4^{2}$-**: sulphate; **As**: arsenic; **Cr**: chrome; **Cd**: cadmium; **Cu**: copper; **Fe**: iron; **Mn**: manganese

Capítulo 3

Discusiones finales, conclusiones y recomendaciones

Como se ha discutido en profundidad a lo largo de este trabajo, los distintos enfoques metodológicos desarrollados para la evaluación del nexo entre recursos adolecen de distintos problemas que dificultan su reproducibilidad y comparación de resultados en distintos contextos geográficos y productivos. Dentro de estos problemas, uno resulta especialmente relevante y debe ser destacado: la mayoría de los estudios se concentran en la cuantificación física de la demanda directa y/o indirecta de los distintos recursos, ignorando la importancia de estimar la eficiencia de su uso, lo que define el impacto sobre el nexo, según el contexto en el que se desarrolle la evaluación. Por otro lado, en los últimos años la exergía ha surgido como una herramienta de excelencia para la evaluación de la sustentabilidad de distintos sistemas. En efecto, dada su naturaleza termodinámica, la exergía logra conectar un sistema con su ambiente mediante distintos indicadores, lo que permite evaluar la calidad, el impacto y eficiencia de estas conexiones. En consecuencia, como se discute a continuación, el uso de la exergía como herramienta de evaluación del nexo entre recursos, en un determinado sistema, permite solucionar en gran medida el principal problema que aquí hemos señalado.

En materia de uniformidad de métricas, la ventaja de usar indicadores exergéticos es evidente. Esto, porque hace posible expresar distintas magnitudes características de un determinado recurso en unidades exergéticas, por ejemplo, MJex (Sistema Internacional). Lo anterior fue demostrado en la práctica en los dos casos desarrollados en el capítulo 2, lo que puede extenderse a cualquier otro caso distinto, independientemente de la escala o contextos asociados.

No obstante, si bien uniformar métricas es un paso muy importante en materia de desarrollo de metodologías reproducibles que otorguen resultados comparables, queda por resolver un segundo elemento de gran relevancia a la hora de evaluar el impacto de los recursos en el nexo: determinar qué tan eficiente es su uso, en términos directos e indirectos, en un sistema sometido a un contexto particular. La exergía ha sido ampliamente utilizada en la literatura técnica para la optimización de procesos térmicos y químicos, donde se han desarrollado una variedad de indicadores de eficiencia. Por otro lado, ante el desarrollo de la relación entre exergía y sustentabilidad se han combinado estos indicadores con métodos que abordan la dimensión ambiental, económica y social de un sistema. En tal sentido, sobresale la integración de los principios del LCA y la exergía, ya que permitieron evaluar, mediante indicadores exergéticos, la eficiencia del nexo entre diferentes recursos. Indicadores como el CExC contabilizan la exergía que un producto va acumulando a lo largo de su cadena de valor, permitiendo clasificar los recursos en directos o indirectos. El CDP es un indicador de eficiencia exergética que, al basarse en el CExC, evalúa la eficiencia en el uso de los recursos por todo el ciclo de vida de un producto.

Por otra parte, la intensidad del nexo puede variar según el contexto socio-económico y las condiciones climáticas. Ahora bien, las actividades productivas y las urbanizaciones situadas en un territorio adaptan su demanda según estas variables. Los resultados del segundo caso de estudio demostraron cómo la disponibilidad y los usos del agua inciden notablemente en la demanda de recursos de los sistemas de producción de agua potable, variables contabilizadas con los índices de WSI, BWF y el CExC. Se intentó evaluar la intensidad del nexo contrastando dichos indicadores, así como identificando sus posibles interrelaciones. Debido a su alta escasez hídrica, las plantas de potabilización local en el norte y centro de Chile recurrieron a tecnologías energéticamente intensivas como la de osmosis inversa, para poder abastecer la demanda de la población. Estas condiciones explican por qué la intensidad del nexo en estas regiones es mayor en comparación con las regiones del sur, donde la disponibilidad hídrica es alta y aún puede suplirse la demanda de diferentes usos.

Adicionalmente, a partir de los casos de estudio desarrollados fue posible determinar que en general el componente agua tiene una aparente baja contribución al CExC total de los sistemas. Esto se debe al bajo contenido exergético del agua en comparación con el valor de los recursos energéticos. Sin embargo, esto puede interpretarse como si el nexo agua-energía de los sistemas evaluados tuviera un bajo impacto en los recursos hídricos.

En consecuencia, se destaca la importancia de complementar la evaluación exergética del nexo con otros indicadores ambientales o metodologías que permitan resaltar de mejor manera recursos de bajo contenido exergético. En lo esencial, la BWF (Silalertruksa and Gheewala, 2018) o el IOA (Guan et al., 2019), podrían usarse para contabilizar la dependencia de las actividades productivas al recurso agua. La BWF se ha utilizado ampliamente en el sector energético para contabilizar la demanda de agua con el enfoque de ciclo de vida (Silalertruksa and Gheewala, 2019; Zhu et al., 2019). Los IOA se han utilizado para cuantificar los consumos específicos de agua en las tecnologías de generación eléctrica y en la extracción de combustibles. Estos métodos se caracterizan por su flexibilidad para evaluar el nexo en diferentes escalas, así como por su capacidad de integrar el suelo (Guan et al., 2019). Para este último, también podría recomendarse la huella ecológica que ha sido utilizada para evaluar los impactos de la extracción de combustibles en la calidad de los recursos terrestres (Akif and Sinha, 2020; Charfeddine, 2017). Según esta discusión, podrían utilizarse varias herramientas para contabilizar y señalar la importancia de estos recursos; aunque su replicabilidad, comparación con casos de estudios y transición entre escalas (desde micro-macro escala) seguirán siendo una pregunta sin responder. De esta manera, puede decirse que la viabilidad de su implementación reside en ser herramientas de apoyo de los indicadores exergéticos para evaluar la intensidad del nexo entre el agua, la energía y el suelo en un determinado sistema.

En conclusión, los resultados de la exergía destacaron la complejidad del nexo, indistintamente de los recursos evaluados y de los casos de estudios, demostrando su fuerte dependencia a las condiciones socio-económicas y geográficas locales. No obstante, es posible que los tomadores de decisiones no entiendan fácilmente los indicadores estudiados, debido a las diferentes dimensiones que caracteriza al nexo. Este problema podría resolverse aplicando el MCDA que admite situaciones complejas de toma de decisiones con objetivos múltiples y a menudo contradictorios. En este contexto, Lee et al., (2018) habían aplicado la toma de decisiones multicriterio para la gestión sostenible de los recursos hídricos en el WELN, considerando criterios económicos y ambientales. Los autores demostraron que la viabilidad económica se consideró el factor más importante en la implementación de las prácticas del uso del agua, donde el control y la gestión del bombeo de aguas subterráneas se clasificaron como acciones de alta prioridad para la gestión de los recursos hídricos. Otros autores también han aplicado el MCDA en el marco nexo (Komendantova et al., 2020; Psomas et al., 2018). Por lo tanto, recomendamos expandir el presente estudio con un enfoque MCDA, que podría ayudar a los tomadores de decisiones a establecer estrategias sostenibles de nexo agua-energía en el CES y DWT urbano.

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