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A Review on Water-Energy Nexus and Directions for Future Studies: From Supply to Demand End

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Abstract

The intrinsic links between water and energy have produced a new concept known as water-energy nexus (WEN), which has been increasingly studied by scholars and global institutions since the 1990s. This paper provides a review of water-energy nexus studies in an interdisciplinary manner starting from two major approaches—*water for energy* and *energy for water*—which focus principally on quantitative studies, but also on policy and institutional dimensions. Many studies mention data collection, the lack of coordination between existing frameworks and the scale/boundary of the two resources as major challenges, whereas new technologies are seen as an opportunity for the nexus perspective. After identifying research gaps, the political ecology approach is proposed for a critical reflection on WEN. Additionally, water poverty and energy poverty (or fuel poverty) are also proposed as part of WEN studies in order to broaden their spectrum to include the demand-end perspective and introduce a social dimension in WEN.

Keywords: water-energy nexus; political ecology; water intensity; energy intensity; households

Resum. *L'estat de la qüestió sobre el nexe aigua-energia i les perspectives futures d'investigació: des de l'oferta fins a la demanda final*

Els vincles intrínsecs entre aigua i energia han originat una nova terminologia, l'anomenat nexe aigua-energia (NAE), que ha estat investigat cada vegada més per acadèmics i institucions globals des de la dècada de 1990. Aquest article presenta una revisió interdisciplinària dels estudis de les interrelacions entre l'aigua i l'energia a partir de dos enfocaments principals: l'aigua per produir l'energia i l'energia per subministrar i tractar l'aigua. La revisió se centra principalment en estudis quantitatius i en les dimensions polítiques i institucionals del NAE. Molts estudis esmenten la recollida de dades, la descoordinació dels marcs interpretatius existents i l'escala o límits de dos recursos com els desafiaments principals, mentre que les noves tecnologies es veuen com una oportunitat. Després d'identificar les àrees deficitàries en investigació, la l'autora proposa l'enfocament de l'ecologia política per endegar una reflexió crítica sobre el NAE. Es proposa també incorporar la pobresa hídrica i la pobresa energètica a les llars com a part dels estudis de NAE, ja que estan relacionades amb aquesta aproximació teòrica. Això permet ampliar l'espectre d'investigacions per incloure la perspectiva de la demanda i generar, així mateix, una reflexió social sobre el NAE.

Paraules clau: nexe aigua-energia; ecologia política; intensitat hídrica; intensitat energètica; llars

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Resumen. *El estado de la cuestión sobre el nexo agua-energía y perspectivas futuras de investigación: desde el suministro hasta la demanda final*

Los vínculos intrínsecos entre agua y energía han originado una nueva terminología, el nexo agua-energía (NAE), que ha sido investigado cada vez más por académicos e instituciones globales desde la década de 1990. Este artículo presenta una revisión interdisciplinaria de los estudios de las interrelaciones entre agua y energía a partir de dos enfoques principales: el agua para producir energía y la energía para suministrar y tratar el agua. La revisión se centra principalmente en estudios cuantitativos y en las dimensiones políticas e institucionales del NAE. Muchos estudios mencionan la recolección de datos, la descoordinación del marco de relaciones existente y la escala y límites de dos recursos como los desafíos principales, mientras que la nueva tecnología se ve como una oportunidad. Después de identificar las áreas deficitarias en investigación, la autora propone estudiar el NAE a partir de un enfoque de ecología política. Se propone también incorporar la pobreza hídrica y la pobreza energética en los hogares como parte de los estudios de NAE, ya que están relacionadas con esta aproximación teórica. Ello permite ampliar su espectro de investigaciones para incluir la perspectiva de la demanda y generar, asimismo, una reflexión social sobre el NAE.

Palabras clave: nexo agua-energía; ecología política; intensidad hídrica; intensidad energética; hogares

Résumé. *État des lieux du nexus eau-énergie et perspectives futures de recherche : de l'offre à la demande finale*

Les liens intrinsèque entre l'eau et l'énergie ont conduit à une nouvelle terminologie désignée par les termesnexus eau-énergie (NAE), qui a été étudié par académiciens et les institutions depuis les années 1990. Cet article propose une revue interdisciplinaire des interrelations entre l'eau et l'énergie à partir de deux approches principales : l'eau pour produire de l'énergie et l'énergie pour fournir et traiter l'eau. L'examen porte principalement sur les dimensions quantitatives et aussi sur les dimensions politiques et institutionnelles de la NAE. De nombreuses études mentionnent la collecte de données, le manque de coordination entre des modes d'interprétation différents et les relations d'échelle et / ou les limites des ressources en tant que défis principaux, tandis que les nouvelles technologies sont considérées comme une opportunité. Après avoir identifié les zones déficitaires dans la recherche, l'auteur propose l'approche de l'écologie politique pour entreprendre une réflexion critique sur la NAE. En relation avec cette approche théorique, nous proposons également d'incorporer la pauvreté de l'eau et la pauvreté énergétique des foyers dans le cadre des études sur le NAE. Cela élargit le champ des enquêtes afin d'inclure la demande et aussi de générer une réflexion sur les aspects sociaux du NAE.

Mots-clés: nexus eau-énergie; écologie politique; intensité hydrique; intensité énergétique; foyers

Summary

1. Introduction

Water and energy are essential for human survival and intimately intertwined (Voinov and Cardwell, 2009). This connection between two resources is called the 'water-energy nexus' (WEN) (Scott et al., 2011). Even though the connection has been well understood and utilized by humans since ancient times in forms such as watermills, the myriad connections between the use of water and energy began to draw attention from academics only from the 1990s (Gleick, 1994; Wichelns, 2017). The main reason for the relevance of WEN is that the distribution of water requires enormous amounts of energy and the production of energy requires equally large amounts of water (King et al., 2008). The increasing demand for energy will put large pressures on limited water resources, creating direct competition between the two resources. Likewise, increasing demand for water to be satisfied with non-conventional resources such as desalination will require more energy.

The need for WEN studies has increased since both resources face scarcity conditions globally. It is reported that 2.8 billion people live in high water stress areas and 1.2 billion people live in areas of physical scarcity (World Water Assessment Program [WWAP], 2012). In terms of energy, 2.5 billion people have unreliable or no access to energy sources. At the same time, global energy demand is continuously increasing. It is expected that the global average energy demand will increase from 81.2 GJ per person in 2012 to 96 GJ per person in 2035, that is, a 40% increase. Especially in emerging economies such as China, India and Brazil, it is estimated that the energy demand will almost double current consumption over the next 40 years. This is challenging because the 35% increase in energy consumption from 2010 to 2035 would correspond to a parallel 85% increase in water consumption (International Energy Outlook, 2012).

Water and energy planning therefore must be based on an in-depth understanding of interdependencies taking into account existing and future water or energy constraints. Unfortunately, there is a lack of cooperation between planners and decision makers in the water and energy sectors and they often remain ill-informed about the drivers of WEN challenges, how to address them, and the merits of different technical, political, management, and governance options (Rodriguez et al. 2013). Several studies have highlighted that much effort is needed to improve the bureaucratic and administrative aspects of planning and management of these two resources and many international organizations and states have addressed WEN as a major topic in high-level conferences (OECD, 2010; World Economic Forum, 2009; WWAP, 2012). Moreover, more academic attention is required to advocate WEN studies (Muller, 2015).

This article aims to compile WEN literature and provide an interdisciplinary review covering quantitative to qualitative studies from various fields ranging from engineering to geography. Some of the challenges and opportunities are highlighted as WEN research often share difficulties derived from the experience where two different resources had to be treated in the same sphere including difficulties in data collection, separated policy and regulatory frameworks, and complexity. But new technologies are being experimented and proposed as possible solutions to these challenges. The article also aims to expand and variegate classic WEN studies by proposing future research directions to perhaps include a more visible notion of the nexus in the demand end ranging from demand management to the lack of resources due to unjust resource distribution, in what is commonly defined as energy poverty or water poverty.

The article also links into political ecology (Robbins, 2007; Peet and Watts, 1996); a broad academic field responding to the need for a critical perspective on WEN (Verhoeven, 2015; Williams et al., 2016). Fruitful insights from political ecology have brought together various fields such as ecology, social science, environmental science and political economy (Peet and Watts, 1996) to provide 'normative understanding that there are very likely better, less coercive, less exploitative, and more sustainable ways of doing things' (Robbins, 2004: 12). Thus, political ecology attempts to enhance our understanding of the relationships between water and energy and political, economic, and social factors.

This review is based on publications from academic journals, state and federal government agency reports, and international organization and non-governmental organization reports on WEN. A few review papers also provided some insight and the state of development of the field (Gleick, 1994; Retamal et al., 2008; Kenway et al., 2011).

In the following section, WEN is explained according to two fundamental conceptual approaches, *water for energy* and *energy for water*. An overview of the research methodologies applied in policy and institutional dimensions and the demand-end of WEN is then provided. We challenge and stretch the boundary of the classic WEN studies by arguing that more focus should be placed on the demand-end, possibly including energy (fuel) poverty and water poverty from the WEN perspective. In section three, the challenges and opportunities drawn from the literature review are outlined. Section four recaps the research gaps diagnosed and conclusions are drawn in section five. Lastly, the review concludes with proposals for future directions for study.

2. The Water-Energy Nexus

The existing research on WEN has covered a wide range of dimensions ranging from technology, environment and economic to social and political/legal issues. Even so, it is widely argued that a systematic understanding of the interrelationship between water and energy is lacking and is needed in order to define an optimal policy or planning for the water and energy sector. The scale of research also varies from the local, state or regional to national levels (Kenway et al., 2011). More recent studies on the macro scale focus on analyzing interrelationships at the national level due to data availability. These studies are quantitative in nature and explore the status quo of the relationships.

In order to understand its complexity and to map the interrelationships, WEN is commonly studied from one side of the resource to another. As said before, these two approaches are respectively called *water for energy* and *energy for water*.

2.1. Water for energy

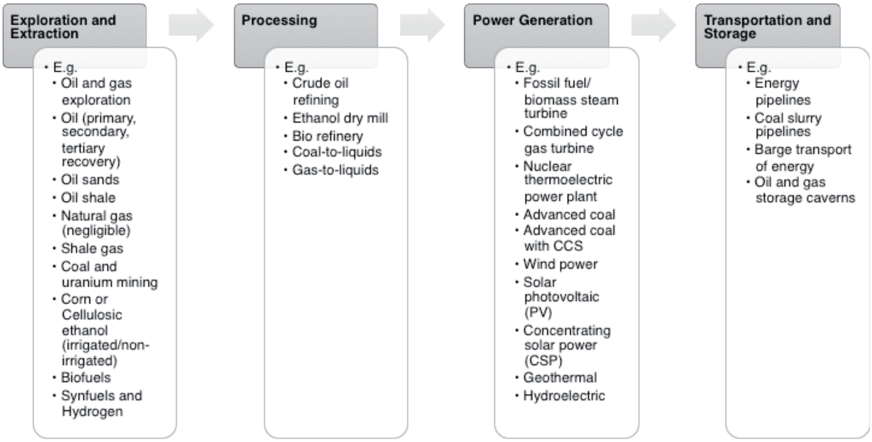
Water is required to produce all kinds of energy sources from extraction including the mining, refining and processing phases to the production of electricity (Table 1). This is a well-studied field given the relative priority and importance of the energy sector (Kenway et al., 2011). Water for energy is most commonly measured by calculating the water consumed per unit of electricity produced (m^3/GWh) either directly or indirectly. Water requirements are usually quantified based on three concepts: water withdrawal, water consumption, and water discharge. Withdrawal is defined as the amount of water taken from a water source (lake, reservoir, river, ocean, aquifer, etc.). Consumption is the water lost from the total water withdrawn through evapotranspiration or degraded due to contamination to such a point that the chemical or physical properties of the water have changed and it is no longer usable and has to be disposed of. Discharge is the amount of water that is returned to the water source although in a different state. It is important to understand that in some cases much of the water withdrawn can be returned back to the source. In summary, water consumption accounts for the amount of water withdrawn minus the water disposed according to the equation:

$$\text{Water withdrawal - Water disposal = Water consumption}$$

The importance of water in the energy sector has been recently highlighted once again as several power plants around the world were shut down due to water shortages. Globally, it is estimated that the energy sector accounts for 10% of the world's freshwater withdrawals mainly for power plant operations and the production of fossil fuels and biofuels (IEA, 2016). However, for countries like the United States, the share increases to 38% when accounting only for thermoelectric power plant water use over annual freshwater withdrawal (Maupin et al., 2014).

Water availability constraints influence the choice of technology, sites, and the type of energy facilities. Conversely, depending on the raw material or the technology selected to generate power, water consumption may vary significantly. Examining the current energy system and deciding on the future energy mix is of enormous importance, considering that water and energy stress is expected to exacerbate due to population and economic growth. Therefore, it is important to consider WEN to guarantee long-term energy provision (Rodriguez et al., 2013).

Table 1. Existing energy sources and technologies



Exploration and Extraction	Processing	Power Generation	Transportation and Storage
• E.g. • Oil and gas exploration • Oil (primary, secondary, tertiary recovery) • Oil sands • Oil shale • Natural gas (negligible) • Shale gas • Coal and uranium mining • Corn or Cellulosic ethanol (irrigated/non-irrigated) • Biofuels • Synfuels and Hydrogen	• E.g. • Crude oil refining • Ethanol dry mill • Bio refinery • Coal-to-liquids • Gas-to-liquids	• E.g. • Fossil fuel/ biomass steam turbine • Combined cycle gas turbine • Nuclear thermoelectric power plant • Advanced coal • Advanced coal with CCS • Wind power • Solar photovoltaic (PV) • Concentrating solar power (CSP) • Geothermal • Hydroelectric	• E.g. • Energy pipelines • Coal slurry pipelines • Barge transport of energy • Oil and gas storage caverns

Source: Mielke et al. (2010).

Water for fuel extraction, processing, and transportation

Primary energy sources like oil, gas, coal, and uranium all require a substantial amount of water in order to be extracted, processed, and transported (Table 2). As oil ages, it requires more water for extraction. Traditional oil extraction methods require 3–7 L/GJ (US Department of Energy, 2006). However, when oil is extracted by unconventional methods such as hydraulic fracturing or fracking, 70–1800 L/GJ of water are consumed (US Department of Energy, 2006). Some authors have argued that oil sand exploration only requires three times more water than the conventional crude oil (Olsson, 2012). Biomass, when it is irrigated and processed to produce bioethanol or biofuel, requires as much as 500 times more water than other types of fuel (Olsson, 2012).

Table 2. Water consumption for raw materials

	Raw material	Water for energy (L/MWh)	Transformation	Water for energy (L/MWh)
Oil	Traditional oil	11–25	Oil refining	89–232
	Enhanced oil Recovery	176–32,143		
	Oil sands	250–6,429		
Biofuels	Corn	32,413–357,143	Ethanol	168–179
	Soy	178,571–964,286	Biodiesel	50
	Sugar	N/A		
Coal	Coal	18–250	Coal-to-liquids	500–786
Gas	Traditional gas	Minimal	Natural gas processing	25
	Shale gas	129–193		

Source: US Department of Energy (2006).

Cooling water

Fossil and nuclear power systems account for 80% of electricity generation. These systems require cooling to condense the steam turbine exhaust and, additionally, for some secondary purposes such as equipment for washing and cooling, emissions treatments, and facilities for workers. Compared to the large volume of water withdrawn and consumed for steam condensing, water consumption for these other water uses is rather small (Table 3).

Cooling systems are key to the water intensity of the power plant and influence power plant efficiency, capital and operation costs, water quality, and total environmental impacts. Open loop cooling systems withdraw large amounts of water and therefore may not be appropriate for water scarce regions although most of these volumes are discharged back to the water source. As long as the quality of the discharged water is appropriately managed, water consumption remains small compared to closed loop systems. Closed loop cooling systems withdraw less water but most of this water is lost by evaporation in the cooling tower. Other alternative cooling technologies such as cooling reservoirs and dry cooling systems are also

Table 3. Water intensity for thermoelectric power plants

Plant type Steam	Process	Steam condensing Withdrawal (L/MWh)	Steam condensing Consumption (L/MWh)
Fossil/biomass/waste	OL	75,708–189,271	~1,136
	CL tower	1,136–2,271	1,136–1,817
	CL pond	1,893–2,271	~1,817
Nuclear	OL	94,635–227,124	~1,514
	CL tower	1,893–4,164	1,514–2,726
	CL pond	3,028–4,164	~2,726
Geothermal steam	CL tower	~7,571	~5,300
Solar trough	CL tower	2,877–3,483	2,877–3,483
Solar tower	CL tower	~2,839	~2,839
Other			
Natural gas CC	OL	28,390–75,708	379
	CL tower	~871	~681
Coal IGCC*	CL tower	~946	~757

OL= Open loop cooling, CL= Closed loop cooling, CC= Combined cycle, IGCC= Integrated gasification combined cycle

Water for other cooling loads such as gas turbine, equipment washing, emission treatment, restroom, etc. which range from 26 to 530 depending on the plant type. Dry cooling systems require 0 withdrawal & consumption.

*Includes gasification process water

**Reference did not specify whether values are for withdrawal or consumption

Source: Adapted from US Department of Energy (2006). Data based on EPRI (2002), CEC (2002, 2006), Leitner (2002) and Cohen et al. (1999).

used in some power plants but their presence compared to the rest of the technologies remains low.

Water for renewable energy

The water requirements for renewable energy that does not require steam engines, such as photovoltaic and wind power, are very low. However, other renewable energy technologies such as concentrated solar power (CSP) and geothermal energy that produces power using heat may be water intensive depending on the cooling technology. Biofuel is one of the most water intensive renewable energy options available. For example, if the share of biofuels for transportation in the Spanish energy mix increase from 1% to 25% by 2030, this would imply the consumption of almost 6 times the total water consumed by the electricity sector in 2005 (Rio Carrillo and Frei, 2009).

Hydropower

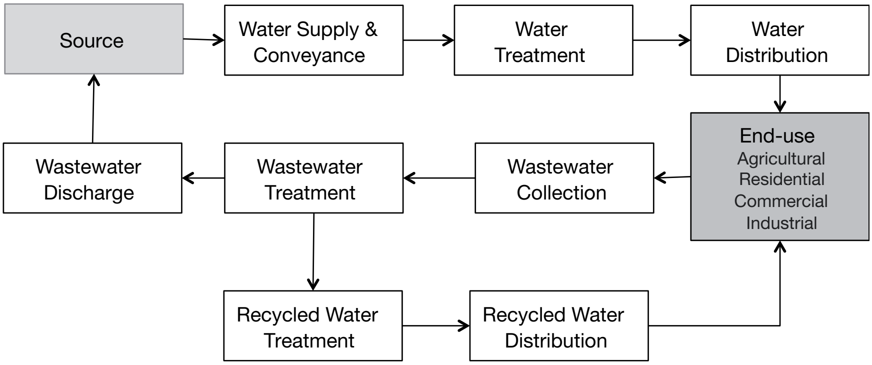
Although large dams are a very attractive source of energy, especially for developing countries (World Bank, 2013), they are considered unsustainable due to environmental and social impacts such as sedimentation, risks from dam failures, changing river patterns, altered ecosystems, and the displacement of people and economic activities. In WEN terms, water loss by evaporation from the reservoirs poses a problem in warm climates. However, this is often overlooked due to the fact that reservoirs will still provide water that would otherwise not be available (Olsson, 2012). The degree of evaporation varies depending on the size of the dam and its location, ranging from 0 to 540 m^3/kWh (IPCC cited by Olsson, 2012; US Department of Energy, 2006).

2.2. Energy for water

Energy for water studies is another side of WEN story where water supply is the central focus. For example, in the United States and China, it is estimated that energy use for water accounts for 4% of the country's electricity generation (Copeland, 2017; Li et al., 2016). Energy is used as water provides for urban, agricultural, and industrial needs through the water supply-use-disposal chain, which can be further divided into various stages (see Figure 1). Not all water uses have the same energy intensity. The energy requirement for supplying water depends on the geographical attribution, quality, and distribution of the water source, as well as the type of technology used for its treatment and mode of disposal. Energy for water, also called 'energy intensity' or 'energy embeddedness', is calculated by computing the energy required per unit of water volume measured (kWh/m^3) for each stage and may be aggregated according to the boundaries defined by each case study. A comparison of case studies demonstrates that the amount of energy consumed varies in specific stages of the water systems conditioned by their geological conditions, technologies, and infrastructures (Wakeel et al., 2016).

In comparison to energy, which is the major water user, energy use by the water sector only accounts for a small portion of total energy use. However,

Figure 1. Water use cycle scheme



Source: Adapted from CEC (2005).

because most countries attempt to reduce greenhouse gas emissions there are ample opportunities for creating a win-win solution for climate change, energy security, and water conservation (Hussey and Pittock, 2012).

Source and conveyance systems

For surface water extraction and transportation, the physical environment exerts a basic influence on energy requirements. Table 4 illustrates different energy intensities depending on the region and type of water extraction. Groundwater pumping has different energy intensities depending on the depth of the aquifer, the pressure and flow rate of the output water, and the efficiency of the pumping system. Commonly, it is assumed that the efficiency of pumping is around 50%. Based on a different approach, EPRI (2002) estimates the energy intensity of source and conveyance systems according to the sector in which the water is used. For example, the unit electricity consumption for groundwater is 0.185 kWh/m^3, whereas for surface water source it is 0.079 kWh/m^3 for domestic, commercial, irrigation, and livestock sectors. For the industrial and mining sectors, 0.198 kWh/m^3 were assumed for groundwater pumping with additional energy requirements such as frictional losses or higher pressures. In the power generation sector, values of 0.211 kWh/m^3 for groundwater pumping and of 0.040 kWh/m^3 for surface water supply were estimated (EPRI, 2002).

When conveyance is required over long distances with elevations, local treatment and distribution, and wastewater collection and treatment, water becomes more energy intensive (Wilkinson, 2000). Energy requirements at this stage of water provision depend on the number and performance of pumping systems required to transfer water from the source to the water purification plant. In the United States, around 4% of the nation's electricity is required for water conveyance, water treatment, and wastewater treatment. Of this use, 80% is for 'moving' water (EPRI, 2002).

Table 4. Energy intensity per water-use cycle in different regions

Stages	Region	Purpose	Energy for water (kWh/m^3)	References
Ground water extraction	USA	Groundwater pumping	0.14-0.79	(Wilkinson, 2000; EPRI, 2002; Plappally and Lienhard V, 2012)
	Australia	Groundwater pumping	0.48-0.53	(Rocheta and Peirson, 2011)
	China	Groundwater extraction (national average)	0.37	(Li et al., 2016)
	USA (Central Arizona)	Lifting groundwater	3.3	(Perrone et al., 2011)
	USA	Whole water supply system	1.02	(Griffiths-Sattenspiel and Wilson, 2009)
Surface water extraction	Australia (Sydney)	Surface water Pumping	0.92	(Kenway et al., 2008)
	China	Water storage & pumping	0.13 & 0.37	(Li et al., 2016)
Water distribution/ conveyance	USA (Northern California & Southern California)		0.04 & 2.4	(CEC, 2005)

Source: Adapted from Nair et al. (2014) and Li et al. (2016).

Desalination

Among the different water sources, desalination is a relatively new and non-traditional technology used to provide potable water from sea or brackish water. Because desalination is extremely energy intensive, it is criticized as being insufficient or maladapted as a new water source (March, 2015; Swyngedouw and Williams, 2016). Even so, in arid areas, such as in the Middle East and North Africa (MENA), desalination plants are the major sources of water supply and they are considered a feasible alternative to fresh water resources (Siddiqi and Anadon, 2011).

Table 5 shows the different types of desalination technologies and energy consumption per technology. There are several technological options available for desalination including thermal processes, such as multi-stage flash (MSF), multi-effect distillation, or mechanical processes, such as reverse osmosis, which is electrically driven. Studies have found that different types of desalination processes have distinct energy requirements. In terms of energy consumption, reverse osmosis (RO) is generally more efficient than thermal processes (Plappally and Lienhard V, 2012), which is also the reason why thermal processes have historically been implemented in countries with abundant energy resources but scarce water (Olsson, 2012). Current state-of-the-art seawater desalination with RO methods requires 3–5 kWh/m^3 and brackish water needs around 0.5–2.6 kWh/m^3. However, MSF typically requires 12–15 kWh/m^3 and up to 25 kWh/m^3 (Olsson, 2012; March, 2015). Attempts to increase the energy efficiency of desalination technology are closely related to direct impacts on operation costs and thus many plants

Table 5. Summary of different desalination technologies and their energy consumption

Type	Technology	Summary	Energy for water* (kWh/m³)
Thermal Process	Multistage flash distillation (MSF)	After heating water, pressure is diminished so that the water ''flashes" into steam. It is the most widely used thermal process.	Pumping: 2.5–5.0 Thermal energy**: 6.8–20
	Multiple effect distillation (MED)	A number of evaporators are installed in series so that the water passes through and vapour from one series is used to evaporate water in the next series. It is the oldest modern desalination technique and is efficient in thermodynamic terms.	Pumping: 1.0– 2.9 Thermal energy**: 3–6.6
	Vapor compression (VC)	Water is evaporated to vapour to be compressed. The heated compressed vapour is used for the next feed of water.	8.0–17.0
Mechanical process	Reverse osmosis (RO)	Membrane screens molecular size to about 1 Angstrom (10-4 microns) and removes salinity from salty water (or brackish water) when it is introduced with high pressure. Recovery rate of the process is usually higher than 60% (ratio of desalinated water over initial water intake).	Seawater RO: 2.0–8.5 Brackish water: 0.5–2.6
	Electro-dialysis (ED)	Electrical field is applied across a set of cationic/ anionic membrane pairs which excite the ions to transfer through the membranes, leaving a stream of desalinated water.	0.8–1.7
	Forward osmosis (FO)	Relatively new process that uses injection of ammonia, carbon dioxide or other ingredients in the draw solution (salt) to increase the osmotic potential. Uses relatively little energy.	
	Pressure retarded osmosis (PRO)	Osmotic pressure is used to generate power where two solutes with different salt concentration are available. Newer technology.	

* Range of energy consumption is the minimum and maximum value of data from various studies over year

** Equivalent electrical energy

Source: Adapted from Olsson (2012), Plappally and Lienhard V (2012) and March (2015).

have deployed renewable energy on site in order to become self-producers of the energy.

Water treatment (water purification)

Energy use for water utilities varies significantly between treatment plants and cities depending on design flow rates, level of treatment, technology applied, source of energy, and scale of plant (Kenway et al., 2008; Rocheta and Peirson, 2011). Moreover, energy consumption for water and wastewater treatment in cities may be affected by local circumstances and regulations (Kenway et al., 2008). Table 6 lists the available treatment technologies applied in the mar-

Table 6. Energy impact of new water treatment technologies

Treatment technology	Energy for water (kWh/m^3)
UV disinfection	0.19–0.26
Nanofiltration (Membranes)	0.476
Ultrafiltration (Membranes)	0.264
Low pressure micro filtration (Membranes)	0.026
Ozone	0.044

Source: Carlson and Walburger (2007).

ket together with their corresponding energy requirements. UV disinfection and membrane technologies are currently replacing chlorine despite its higher energy intensities.

More concretely, cases from the United States have shown that surface water treatment facilities that use processes including rapid mix, flocculation, sedimentation, and filters of 37,850 m^3/day have an estimated total electricity consumption of about 14,057 kWh per day, which is equivalent to a unit energy consumption of 0.371 kWh/m^3 (EPRI, 2002). This study found that variations are driven primarily by economies of scale, particularly in the case of small facilities, where unit electricity consumption decreases as the size of the treatment plant increases. Regardless of size, however, electricity is primarily used for pumping treated water into the distribution system, which normally accounts for between 80 and 85 percent of the total electricity consumption for surface water treatment (EPRI, 2002).

Distribution to end-users and waste collection

Energy is required in order to distribute water to the end-users. These distribution systems are usually equipped with chlorination points to meet the regulations on chlorine levels at the faucet for potable uses. When reservoirs are located in sufficiently higher places, gravity pressurization and distribution is also possible (Cohen et al., 2004). Depending on the location of the waste treatment plants, waste collection could also require energy for moving water through pipes.

Wastewater treatments

The average energy consumption per cubic meter of wastewater treated, regardless of the technology applied, does not differ much across countries as it ranges from 0.36–0.67 kWh/m^3 (Hernández-Sancho et al., 2011). However, when the volume of water treated in each country is considered, the difference in the net energy use could be significant. Economies of scale can generally be achieved at this stage. However, unit electricity consumption is higher as the degree of treatment and complexity of the process increases due to augmented salinity and organic material contents in the wastewater (Hancock et al., 2012). The highest energy consumption in wastewater plants is due to the aeration process (CEE, 2007). According to ICF Inter-

Table 7. Energy intensity for wastewater treatment plants in the United States and Australia

United States	**Energy for water (kWh/m^3)**
Trickling filter	0.252
Activated sludge	0.348
Advanced wastewater treatment without nitrification	0.407
Advanced treatment with nitrification	0.505
Australia	**Energy for water (kWh/m^3)**
Primary treatment	0.22
Secondary treatment (removal of C, including primary treatment)	0.46
Tertiary treatment (removal of C, N, and P, including secondary treatment)	0.90

Source: EPRI (2002) and Kenway et al. (2008).

national reports for the US EPA in 2008, it is possible to save 15% to 30% of electricity by installing high efficiency motors and pumps (cited in Water in the West, 2013).

At the national level, the energy intensity of wastewater treatment depending on the type of treatment facility has been calculated in the literature.[1] Unit energy consumption for water supply and wastewater treatment per plants are provided in Table 7 for the United States and Australia.

On average, energy intensity doubles between each treatment phase. Thus, it doubles between the primary and secondary treatment and doubles again between the secondary and tertiary treatment. Advanced wastewater treatment requires relatively more energy because of additional pumping (EPRI, 2002). After the tertiary treatment of wastewater, re-use opportunities may become more cost-effective as the additional energy required for re-use may be relatively small depending on energy requirements after treatment (Kenway et al., 2008).

Water end-uses

End-use energy intensity for domestic water is reported to be as high as 72% of the total water cycle (Plappally and Lienhard V, 2012). Among other household activities, water heating comprises 97% of total water-related energy use and is therefore of considerable importance (Arpke and Hutzler, 2006; Flower et al., 2007). According to Kempton (1988), energy use for water heating ranged from 1.8 to 4.7 kWh/day. In hot water use, behavioral and cultural

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1. Primary treatment removes large solids (e.g., rags and debris) and smaller inorganic grit and is the first stage of each of the four representative processes (screening and settling). Secondary treatment removes organic contaminants using microorganisms to consume biodegradable organics (e.g., activated sludge or trickling filters). Advanced treatment systems go beyond secondary treatment to include nitrification (to convert ammonia to nitrates), denitrification (to convert nitrates to nitrogen), physical-chemical treatment (to remove dissolved metals and organics), and/or disinfection (to kill any remaining pathogens) (EPRI, 2002).

aspects of individuals and their demand for water have an important influence (Plappally and Lienhard V, 2012). The geographical situation and climate influence the energy input for heating water because colder inlet temperatures require more energy for heating (Gutierrez-Escolar et al., 2014). Other factors include habit, time of year, purpose of the building, temperature of cold water, temperature of domestic hot water (based on the European standard of 60 degrees Celsius), type of building, number of members in the household, and others (Gutierrez-Escolar et al., 2014). In Spanish residential buildings, energy consumption from domestic hot water accounts for about 20% of total energy use. Annual average domestic energy consumption for hot water is 1755.90 kWh per household and average water consumption is 142 L per capita per day.[2] In Australia, 0.2% of the total energy consumed is used by the water utilities but heating water is responsible for 25% of the residential energy demand and 27% of the greenhouse gas emissions in households, excluding transportation (Kenway et al., 2008).

Lost water (non-revenue water)

When water is lost, especially in urban areas, energy is lost as well. This lost water is called non-revenue water (NRW). Leakages are known to be main reason for losing water. Various studies estimate between 45 and 88 million m^3 of water are lost per day worldwide from the leakages in the water supply systems; that is, enough water to serve some 200–400 million people (Olsson, 2012). In addition to this amount, there is also water loss due to apparent (commercial) losses, among them meter inaccuracies, data mismanagement, or illegal connections. In order to reduce the level of NRW, poor utility performance needs to be improved, ageing infrastructure needs to be replaced and, when installing new piping, additional sensors have to be put in place to improve monitoring.

2.3. Research methods

Most of the research on WEN approaches the study of the relationship from an engineering perspective that uses quantitative analysis based on national data to provide a view according to one resource or from both. Some research focusing on the community or household level has developed methods for bottom-up data collection (Perrone et al., 2011). The methods used to analyze WEN include accounting (Gleick 1994; Kenway et al., 2008), life cycle assessment (LCA) (Muñoz, et al., 2010; Meldrum et al., 2013; Hancock et al., 2012), regional or community models (Rio Carrillo and Frei, 2009; Perrone et al., 2011), spreadsheet models (Wilkinson, 2000), case studies (Cohen et al., 2004; Kenway et al., 2008; Siddiqi and Anadon, 2011), and GIS (Wilkinson, 2000).

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[2] Banco Público de Indicadores Ambientales (BPIA). Available online: <http://www.mapama.gob.es/es/calidad-y-evaluacion-ambiental/temas/informacion-ambiental-indicadores-ambientales/banco-publico-de-indicadores-ambientales-bpia-/> (accessed on 11 September 2014).

It is increasingly noted that the nexus concept has to be understood at multiple scales such as facilities, cities, and regions (Retamal et al., 2008). Until very recently, the most commonly used methods have been accounting and case studies, but LCA is currently gaining popularity (Wang and Zimmerman, 2011).

Depending on the method used, the boundary of the selected consumption varies. For example, the whole system approach takes direct inputs into account but secondary and tertiary impacts (negative or positive) are not considered, despite the fact that these studies attempt to address environmental and economic implications and benefits. A broader analytical approach is useful for water managers and decision makers who are seeking to comply with regulatory requirements and policies to manage multiple objectives in cost-effective and economically efficient ways. On the other hand, life cycle assessments account for both direct and indirect inputs of resources (Retamal et al., 2008). For this reason, they are commonly used for analyzing WEN at micro scales (e.g., particular technologies, specific end uses, etc.) and they can effectively assess other environmental impacts. However, these assessments present difficulties in downscaling as they use national economic data as the main source.

Some studies incorporate regional or state scenarios or energy mixes to test sensitivity and make future projections for WEN (Rio Carrillo and Frei, 2009). Predictive modelling is applied to take into consideration climate variability, meteorology, and hydrology for improved energy and water resources planning (Hightower, 2006; Hoffman, 2010). Visual display tools, such as GIS, causal loop diagrams, and Sankey diagrams of WEN, facilitate a holistic understanding of water and energy consumption in terms of its distributional and relative consumption levels.

In addition to qualitative methods which tend to focus on supply and the point of use, a broader research question was proposed by other academics that took into account the governance, policy, and institutional dimensions of WEN. Their research revealed managerial challenges for decision makers, which make the full application of WEN difficult.

2.4. Policy and institutional dimensions

Even though the connectedness of water and energy is widely accepted, water and energy have been traditionally planned and managed separately. As tradeoffs between energy and water are becoming increasingly recognized, an important goal for academia remains to change the policy arena for effective implementation of water and energy policies. According to some, integrating sustainability science helped to improve WEN policy development in the United States (Stillwell, 2015). Research should be promoted to influence energy mixes for the future and also the selection of technology for water scenarios. Much of the difficulty in policy development and in fostering conversation between the two fields lies in the fact that the existing policy and institution framework is already fragmented. Moreover, tendencies towards inertia impede radical changes in institutional and personal behaviours (Hussey and Pittock, 2012).

For the water sector, the common understanding is that the water supply and distribution management is essentially a local issue as water is managed in many parts of the world at the municipal level, such as in water saving and efficiency programs. Thus, while analytical boundaries are set at a local level for water, energy boundaries unfortunately do not coincide much with the local sphere. Energy is managed at national level and in most countries depends on reserves that are concentrated in certain regions around the world. In other words, even though water and energy may be commodities with a close relationship, they share a fundamental difference: water is almost always local, whereas energy may be global and remains clearly linked to fungible commodities (Mielke et al., 2010).

Scale is an interesting perspective to consider in WEN as Scott et al. (2011) reported in a case study where local challenges lose importance when considered from broader perspectives. Conversely, regionally important challenges are not prioritized locally. Hence, there is a mismatch in translating challenges appearing at certain scales to institutions created for other scales. Moreover, energy suits the regionalization of adaptation to global change while water does not, as many of the impacts on water availability and quality remain local. Improved coordination between water and energy policy is needed and therefore WEN should be viewed in the light of institutions and decision-making approaches, and not just as a resource management issue (Scott et al., 2011).

In terms of planning, water utilities stress that regions should focus on increasing investment in water-efficient electricity generation, for example solar photovoltaic, wind power and coal gasification systems (Rio Carrillo and Frei, 2009). The linkages between efficiency improvements in water and energy use and the potential multiple benefits to be derived from them have been widely studied in California (Wilkinson, 2000). Water conservation measures are generally advocated as a means to reduce overall electricity consumption with varying impacts depending on the region (Bartos and Chester, 2014). Efficient water and energy use, and the facilitation of cost-effective measures to improve the efficiency of both, are important policy challenges and opportunities. Considering multiple benefits from integrated strategies provides potential opportunities for policy development (Wilkinson, 2000).

However, WEN research in the aforementioned arena does not fully consider impacts on the demand side. Rather it limits its role to the managerial problems of the water and energy supply. In order to have a holistic notion of WEN, the following section looks at the connectedness from the demand angle and its policy implications.

2.5. Demand side

WEN research has focused on the connectedness of both resources from the supply side. In contrast, demand has rarely been managed or controlled until recently even though it exerts a significant influence on the use of resources. Demand has been treated as a given when the the demand side of WEN could potentially bring additional insights into understanding the interconnectedness between the two vectors (Voinov and Cardwell, 2009). It is only very recently that one study proved that applying the ISO 50001 Energy Management System to water produced positive results on the demand side of water use management, like it would for energy use (Walsh et al., 2015).

The statistics of resource consumption demonstrates that domestic water and energy consumption varies largely between countries. For example, Australia uses 341m^3/cap/year in domestic water consumption and ranks as the world highest consumer followed by Canada with 279 m^3/cap/year and the United States with 217 m^3/cap/year. In comparison, the Chinese only consume 26 m^3/cap/year and the Germans 66 m^3/cap/year (Voinov and Cardwell, 2009). However, in addition to domestic water consumption, a significant amount of water used is not accounted for which corresponds to non-consumptive water use for thermal electric power for domestic use. For example, in 2010, the United States needed to extract 72 L of water for each kWh of electricity consumed.[3] It is also interesting to note that this indicator does not correlate with economic development as European countries would always tend to have lower levels of consumption than, for example, North America (Chapagain and Hoekstra, 2004). The same trends apply to the consumption of energy and other goods. Regardless, demand growth has a positive feedback that inflates itself as additional goods and services provided to meet new demands require additional infrastructure and maintenance (Voinov and Cardwell, 2009).

Today, much of the focus on demand management has been in the form of energy-saving regulations or voluntary and domestic efficiency programs. Increased efficiency is critical to attain the sustainable use of both resources as improved water efficiency reduces power demand and improved energy efficiency reduces water demand. Furthermore, in theory both will reduce the costs of water and power for consumers (Stillwell et al., 2011).

With time, it is foreseen that the focus will shift from the technical and engineering arena to the socio-psychological domain. Actually, the real limitation of the demand side of water and energy issue is that producing and selling energy and water is still viewed in many countries as means to generate profits, either benefiting the private sector or generating tax revenues (Voinov and Cardwell, 2009). This could imply the existence of a marginal population unable to access water and/or energy because it cannot be afforded (March and Sauri, 2017).

3. Challenges and Opportunities

3.1. Data collection

One of the main challenges in studying WEN is due to data availability, accessibility, and quality since much of the data are missing, unconsolidated, and

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3. USGS, Thermoelectric Power Water Use <Water.usgs.gov/watuse/wupt.html> (Accessed on 5 October 2016)

imprecise. Some of the early studies on WEN were conducted in the United States by the Department of Energy (DOE), Electric Power Research Institute (EPRI), California Energy Commission (CEC) and the Pacific Institute. A great deal of the data that was produced from their reports has served as the basis for other research on WEN. Other data sources are national statistics offices or utility companies. When research is targeted at a lower scale, such as community, facility or infrastructure, bottom-up approaches have been developed for data collection (Perrone et al., 2011; Bartos and Chester, 2014).

Additionally, data collection in the water and energy sectors could be further strengthened to improve interactiveness, usability, and quality for stakeholders. Data sharing is an operating principle for any data access regime from which common goals and needs can be identified. Good data sharing would provide a firm basis for integrated planning. Priority must be given to data availability, usability, and quality in order to foster effective communication between administrators and policy makers in both sectors (Goldstein et al., 2008). When such data are not publicly available, research on WEN would be a good starting point to foster the discussion for the need of such data.

3.2. Existing policies and regulatory frameworks

The current policies and regulatory frameworks in the water and energy sectors are fragmented because there is a lack of integration between key agencies and sectors in the planning phase in the water and energy institutions. Thus, inconsistencies in the legislation on water and energy management abound, as they do in the legislation for each resource separately. In the United States, for example, water efficient technology and energy efficient technologies were promoted separately, and subsidies were actually driving the implementation of inefficient energy and water technologies (Cohen et al., 2004). Additionally, differing political agendas, visibility concerns, and power rivalries across ministries or agencies put too much effort into unproductive tasks and resulted in inefficient resource uses (King et al., 2008). Ongoing review and evaluation mechanisms should be implemented to identify these and other problems (Scott et al., 2011).

However, as cultural inertia and path-dependency makes water and energy ever more distant, it makes integrating water and energy management crucial to consider WEN. The two sectors have always operated independently and there is a (natural) resistance to their integration. A ‘silo mentality’ in the research community prevents greater integration of research, which then flows through to policymaking. The attitude that engineering and technical solutions are optimal remains dominant at the expense of more holistic solutions. (Hussey and Pittock, 2012).

Bazilian et al. (2011) proposed three approaches to support integrated policies and programs that would properly reflect on WEN. The first is to frame the issue around strong political ‘motivators’ such as lack of access, rather than purely in terms of environmental impacts. The second is to build institutional capacity to understand and act on the complex interactions; and third, to develop and apply modelling tools that can support integrated decision making.

Zhang and Vesselinov (2016) proposed a bi-level approach as a solution to achieve optimal WEN management whereby upper-level decision demands are satisfied first in a top-down decision making process. Their model quantifies the tradeoffs between the two-level decision makers in WEN management.

3.3. Complexity of nexus

WEN is often expanded to include themes such as food, land, and climate change, namely carbon emissions (Rico-Amoros et al., 2009; Bazilian et al., 2011; Yang and Goodrich, 2014; Biggs et al., 2015; Wong and Pecora, 2015; Cairns and Krzywoszynska, 2016; Gallagher et al., 2016; Wanjiru et al., 2016; Vanham, 2016; Wichelns, 2017). As the nexus incorporates more themes, it becomes more difficult to disentangle interconnections. This translates into more difficulties in managing nexus at the policy-making level as the greater involvement of different sectors would slow down the process, causing delays and adding inertia (Wichelns, 2017). Nevertheless, research on these complex relations is important as misunderstanding the interrelation between the two resources could add a greater stress to either one of them or to both.

3.4. New technologies

Underlying the motive for new energy technology, a strong drive comes from ensuring security by extracting resources that before were technologically or economically unviable. When these technologies are considered in the WEN context, it becomes highly questionable whether they are worthy at all. For example, the risk of fracking is very high in terms of the impact it may have on water resources, although little evidence of this has been collected until today (Vidic et al., 2013). Biofuels would also be a water intensive energy alternative, especially when they are produced with irrigated farming (Hardy et al., 2012).

Notwithstanding the above, new technologies also provide innovative applications for WEN. For example, applying solar heating systems would significantly save energy for supplying domestic hot water (King et al., 2008). Photovoltaic or wind power plants are built along with desalination plants in order to produce energy that could be either sold or consumed for part of the electricity needed for processing water (Siddiqi and Anadon, 2011). Some pilot studies have been conducted to combine wave energy with desalination plants (Viola et al., 2016). A number of Win-Win scenarios for attaining both energy and water security are proposed, taking advantage of technologies that are relatively new; for example, low-flow fixtures, energy-efficient appliances, rainwater collection for non-potable uses, solar hot water heating, geothermal heat pumps, electricity peak shaving as a demand response method, solar PV power, wind power, combined heat and power (CHP), hydropower, and con-

Table 8. Emerging water service infrastructure and energy sources

Objective	**Technology**
Water efficiency	Low flow showerheads, dual flush toilets, tap flow regulators, and efficient washing machines and dishwashers
Source substitution*	Rainwater harvesting, stormwater harvesting, greywater recycling, wastewater recycling and groundwater/aquifer (integrated use of all possible options in this table)
Emerging sanitation systems	Alternative sewerage systems – Reduced inflow gravity sewers (RIGS), Septic tank effluent disposal systems (STED), Innoflow interceptor tank – Orenco sewer – AdvanTex treatment pod system, Pressurized sewer systems, Vacuum sewers, waterless technologies
Pumps	Rain tank pumps, submersible septic tank effluent pumps, macerator pumps with pressure sewers and house pumps
Alternative energy sources	Wind farm and solar farm in catchment land reservations with low visual impacts, using access reservations for solar generation, biogas production from sewage treatment and placing small-scale hydroelectric turbines

* Source substation is the application of the “fit for purpose” or “water quality cascade” principle, which seeks to match the quality of the water supplied to where it will be used.

Source: Adapted from Retamal et al. (2008).

verting municipal waste to energy (King et al., 2008). Rainwater harvesting in hilly areas would not only provide water to residents but also offers solutions for energy conservation (Chiu et al., 2009). A list of emerging water service infrastructures and energy sources is provided in the table 8.

4. Research Gaps

4.1. Urban landscape and cities

The importance of studying the interdependence between water and energy is widely recognized in the context of ensuring security for the two resources in both developed and developing countries (Nair et al., 2014; Retamal et al., 2008; Cohen et al., 2004). It is estimated that some 75% of the world population could face water scarcity in the future as demand for good quality water in urban areas will increase substantially (UNESCO, 2012). However, our understanding on the ‘complex and pervasive’ connection between water and energy in cities remains very limited and rudimentary (Kenway et al., 2011).

According to Kenway et al. (2011), urban metabolism provides the conceptual framework to understand urban systems considering the mass balances of all materials, water, and energy. However, more research on urban systems is necessary to enable a valid comparison of populations and their metabolic performance. Some research areas that need further studies concern building a systematic description of the multiple points of connection within cities or within urban landscapes more generally. There is an insufficient understanding of WEN in cities and broadly in urban landscapes, thus few studies have studied the nexus at this scale (Fang and Chen, 2017; Lam et al., 2017). Furthermore, research on the optimization of water and energy systems is almost non-existent even though there are fervent calls for optimization and collaboration in the water and energy sectors.

4.2. Scale of the research

Kenway (2011) observed that in terms of spatial scale, a range of studies have been conducted for appliances, households, buildings, facilities, catchments, cities, states, and nations geographically concentrated in the United States (Stillwell et al., 2011), Australia, New Zealand, and Canada, while some studies can be also found for countries of Europe (Murgui Mezquita et al., 2009) and Asia (McDonnell, 2013; Gu et al., 2014; Keskinen et al., 2016) with a strong drive from China (Gu et al., 2014; Smith et al., 2016; Zou and Liu, 2016; Smith et al., 2017).

No specific study at the global level was found on the interconnectedness of water and energy. In terms of temporal scales, no studies have been performed probably because of the difficulties involved in collecting data over time. Only a few studies have addressed the urban energy implications of the combination of on-site decentralized and centralized water systems operating simultaneously (Retamal et al., 2008). Urban metabolism has been widely studied in the past forty years using models that address the flows between economy and environment, but the relationships between the elements at vertical and horizontal scales require further exploration (Holmes and Pincetl, 2012).

Although studying WEN at the municipal or community level is important for sustainable resource management, studies in this regard are rarely conducted compared to analyses of WEN at national or state levels, again probably due to data availability issues (Perrone et al., 2011). WEN research at lower scales is more apt to draw attention to the possible local collaboration in two sectors and for the better implementation of policies with a reflection on local geographical conditions, notwithstanding the fact that some local jurisdictions are impeded by national policies due to scale mismatches. According to this perspective, especially the collaboration between the two sectors at the municipal level can provide lessons which could give rise a bottom-up approach to influence national policies.

4.3. Demand-end WEN

As WEN relies on national statistical data, its approach is mainly from the supply side, which focuses on withdrawal or exploitation, treatment, supply and delivery, and water recollection and disposal. Thus, the approach remains partial as it neglects or fails to analyze WEN at the demand end. Much of this information and data are difficult to incorporate in the analysis when the supply side approach is taken. Moreover, considering that both water and energy are resources with significant efficiency and management dimensions, the study of WEN from the demand end deserves more attention from academics in the field.

WEN studies focusing on the demand end use data collected from the household (Wanjiru et al., 2016; Vieira and Ghisi, 2016), commercial or industrial sectors (Thiede et al., 2016), including tourism (Becken and McLennan, 2017) and municipal sectors, and are highly likely to be conducted using a bottom-up data collection process. This may allow effectively addressing social issues; for example, the relations between energy (fuel) poverty and water poverty, and might be able to find technological means for reducing poverty in water and energy (Vieira and Ghisi, 2016). But to achieve this goal, we need further research on interactive demand management and the water-energy nexus relationship.

4.4. Critical analysis on WEN

Most WEN studies have concentrated on unravelling the interrelatedness by quantifying water for energy and energy for water. These studies conceptualize nexus bounded to quantified numbers, where emphasis is placed on trade-offs and improved efficiency at its best summarized as 'saving water saves energy' (Copeland, 2017: 2). This type of research often conceives nexus as a managerial tool (Cairns and Krzywoszynska, 2016). Under its dominant theoretical framework, WEN transmits a rather limited and reduced picture of the WEN reality. Whereas WEN is often explained in a static and two-dimensional fashion, the political ecology framework allows for an in-depth analysis of the dynamic and multiple social and political aspects at interplay in the nexus. As Williams et al. (2016) stated, politicizing the nexus would enrich our understanding of the nexus. These authors focus particularly on the capacity of political ecology to capture the essence of human-nature relationships. Such an approach, which mobilizes an emergent, critical and theoretically informed understanding of the water-energy nexus, is developed through a historical process of *coproduction as* 'fundamentally processual and socio-technically heterogeneous' (Williams et al., 2016: 4).

5. Conclusion

This review has attempted to cover areas that are already well researched in the WEN literature and other areas for which knowledge gaps still need to be filled. WEN research is capturing the increasing attention of a number of government and international organizations. Scholars in the field are hopeful that with the right data and with multi-stakeholder engagement, it will be possible to achieve the goal of making water and energy systems more resilient by applying conservation measures and innovations in policy, market, and technology (King, 2013).

It must be remembered that 'no panacea exists' for solving WEN issues. But answers to WEN issues for energy in terms of the water perspective would depend on the local context (World Economic Forum, 2009). Moreover, in order to address increasing interdependence, greater attention is being paid to integrated resource planning, location of water and energy facilities, and systems thinking at multiple scales (e.g., facility, city, and region) (McMahon and Price, 2011: 184)

The study of WEN has to deal with imperfect data availability. Thus, much effort by researchers is still needed to evaluate the actual water and energy consumption of countries, urban areas, decentralized facilities or systems, and non-traditional technologies that are starting to gain popularity. Research across time scales, such as comparisons of current and past WEN, remains an understudied area. Moreover, research is needed to analyze WEN in closely unravelling the tradeoffs between the two resources given various types of policies, institutions, capital, technology, and cultural and religious conditions.

A broader framework provided by political ecology is proposed to help position WEN in the social context and the relationships between two resources that are constantly evolving in a dialectical process. Such a framework would be able to provide a normative understanding that is not limited to the physical relations of nexus, unlike most studies which grant more importance to quantified versions of the nexus, especially in relation to the efficiency of resource use. In other words, it will allow expanding the scope of WEN to reveal a variegated reality of the nexus, which is physical but also social, economic, and political and which therefore requires a holistic understanding with an equal imperative as when water and energy are treated separately.

6. Future Research

Other than exploring WEN for specific sectors (tourism, for instance) and localities, a major topic for future research is to focus on the demand end of WEN, not only to complete both the supply and demand sides of the story, but also to insist on the importance of rebuilding the connection of humans, society, and basic rights to the resource as Linton (2014) would emphasize. This means that a rather ambitious research approach is necessary; one which would cover institutional, social, technological, cultural, economic, and political dimensions that form the context of our understanding of resources from the analysis of the water cycle from the supply (from extraction to end-use) to the demand end (from the perspective of users and households). Unfortunately, 'modern' concepts have often perverted social values and made us believe that we are able to appropriate and manipulate resources without a holistic understanding of the social consequences. Rather naïve and optimistic expectations have brought ecological modernization theorists like Mole, Sonnenfeld and Spaargaren to claim that environmental challenges can be solved through continued industrial development, since the increase in efficiency from the development would eventually exceed the increase in overall production (cited in York and Rosa, 2003). Hence, we dispute their claim by studying the unequal power of the population that, from the demand end, worries about not being able to consume enough water and energy. A case study may reveal WEN experienced by them regarding the problem of limited accessibility, affordability and efficiency and its relation to power struggles. It may also enlighten us with some findings on how these resources are managed in the urban socio-environmental context and how benefits and costs are socially and spatially distributed.

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