Energy and Water Autarky of Wastewater Treatment and Power Generation Systems

Article *in* Renewable and Sustainable Energy Reviews · January 2015

DOI: 10.1016/j.rser.2015.01.055

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Renewable and Sustainable Energy Reviews 45 (2015) 52–68

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

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A R T I C L E I N F O

Article history:
Received 1 August 2014
Received in revised form
5 January 2015
Accepted 12 January 2015

Keywords:
Wastewater
Power plant
Desalination
Energy-water nexus
Self-sufficiency
Cooling water

A B S T R A C T

The energy-water nexus of the water supply, wastewater treatment and power generation systems has been well discussed. It is very clear that one source cannot be produced or supplied without involving the other source. Since the two systems are intertwined with mutual needs, it is difficult to resolve the issues associated with them in isolation. However, combined solutions through integrated approaches may not be feasible in all situations. Therefore, it is important to consider the energy or water autarky (self-sufficiency) of these systems. If these systems can achieve autarky for the energy and water needs independently, such configurations can be considered sustainable. This review paper presents the energy and water needs for water supply, wastewater treatment, and power generation systems and critically examines the potential opportunities for achieving energy and water autarky in these systems. A detailed view of the water supply and wastewater treatment systems' energy footprint was presented and similarly the water footprint of various power plants. Different approaches for achieving energy autarky in the wastewater treatment systems as well as approaches for water autarky in the power generation systems were discussed. It is imperative that future developments should consider an integrated design approach to improve the overall system autarky by communicating between the two individual systems, by considering synergistic energy-water production, by collaborating resources planning and energy-water infrastructure synergies supported by science and system-based natural resource policies and regulations.

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http://dx.doi.org/10.1016/j.rser.2015.01.055
1364-0321/

1. Introduction

Providing affordable drinking water sources and reliable wastewater treatment have become major challenges in many parts of the world [1]. Escalating energy demands for wastewater treatment due to population growth and high living standards and the water demands for power generation combined with environmental degradation present complex and intertwined concerns for many local governments [2,3]. On the other hand, water withdrawals for various uses have increased by 2–3 times that of population growth mainly linked with high living standards and urbanization [4]. It is important now to examine the autarky of the individual systems in terms of energy and water resources. The autarky of the system defines the use of external sources required to sustain the processes intended for certain benefits. For example, wastewater treatment requires between 0.3 and 0.6 kW h/m^3 while the same contains an energy content equivalent to 10 times that required for treatment [5–7]. Therefore, it is logical and rational to develop process configurations that would allow for extraction of this hidden energy to improve the self-sufficiency of the processes. Similar approaches can be implemented for power generation systems as well. In this review article, the potential for self-sufficiency of water-energy systems to provide a sustainable solution is discussed. The self-sufficiency of these systems can be defined as the ability to support each other with minimal dependence on new resources. Utilizing renewable energy sources would further advance their independence from fossil-derived electricity. This paper will first describe the energy usage patterns in water and wastewater treatment systems and the water requirements for power generation systems followed by an analysis and discussion of potential pathways for achieving autarky among the systems for both water and energy production.

2. Energy for water supply and wastewater facilities

Out of 200,000 drinking water treatment systems in U.S., about 25% of the systems serve 25 or more people throughout the year [8]. About 85% of the U.S. population is served by nearly 5% of large-scale drinking water systems; the remaining 95% include a large number of small and very small systems serving 3300 persons or fewer. Most of these systems are owned and operated by Public agencies while a small number are privately operated. On the other hand, over 75% of the U.S. population (~223 Millions) is served by nearly 16,583 public wastewater treatment plants [9]. Nearly 70% of the facilities are small, serving only 10% of the U.S. population and 22% are large (with flow greater than 1 million gallons per day, MGD) and serve over 85% of the population. Both water and wastewater systems require energy in the form of electricity for collection, conveyance, treatment, and distribution for end use or consumption and disposal.

Fig. 1 shows the range of energy requirements for treating different water sources. Conventional water treatment process via coagulation-flocculation-sedimentation-filtration involves energy consumption between 0.25 and 1.0 kW h/m^3 from river water and groundwater sources and most of it accounted for pumping, transportation and distribution. It is interesting to note that the wastewater treatment requires energy in the range of 0.5–2.0 kW h/m^3,

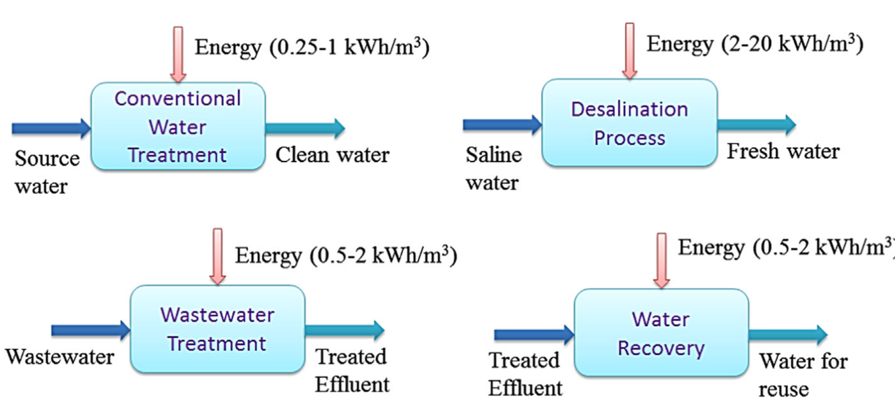

Fig. 1. Energy requirements for water production from different water sources (1 kW h/m^3 = 12,922 BTU/1000 gal).

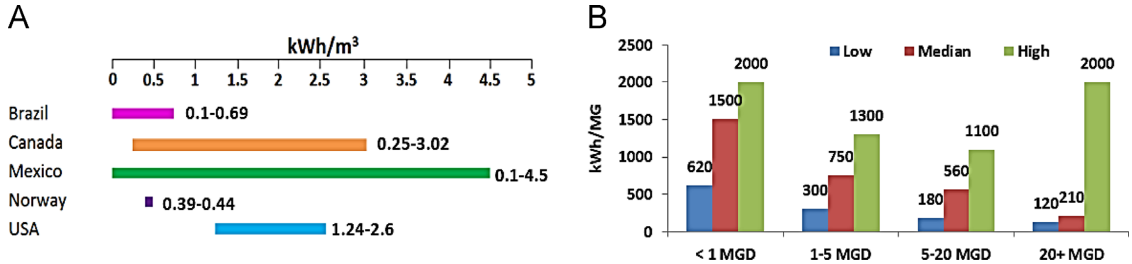

Fig. 2. (a) Specific energy consumption for drinking water production from groundwater and surface water sources; (b) for wastewater treatment for different plant capacities.

most commonly, and less than 0.5 kW h/m^3 for processes without nutrient removal. On the other hand, the regions with adverse water scarcity depend on brackish and saline water sources. These desalination processes consume large quantities of thermal and/or electrical energies for separation of freshwater from saline water reserves, which are between 2 and 20 kW h/m^3 [10]. These regions often recycle wastewater by processing it through an advanced treatment process for nutrient, contaminant, and pathogen removal. Again, these processes are energy intensive with specific energy consumption between 0.5 and 2.0 kW h/m^3.

2.1. Energy for clean water production (conventional water treatment)

Provision of clean water may not be possible without any energy investment (see Fig. 1). Even if freshwater is readily accessible under the ground level, energy is required to pump the freshwater from its source. Freshwater drawn from the groundwater source requires 0.14–0.24 kW h/m^3 (0.5–0.9 kJ/kg) for a pumping head of 100–200 ft. Conventional treatment of surface waters to potable quality requires 0.36 kW h/m^3 (1.3 kJ/kg) [3]. Conventional treatment of water sources (direct chlorination, filtration or chemical coagulation-flocculation, sedimentation, filtration) is only applicable in areas where adequate surface and ground water resources are available. It is interesting to note from Fig. 2a that some water treatment plants consume as much energy as needed to treat equivalent amount of seawater through desalination process like reverse osmosis. In Canada, the energy requirements for firewater supply vary between 0.25 and 3 kW h/m^3 while in Mexico, it is between 0.1 and 4.5 kW h/m^3 [11]. This intense energy consumption stems from the long distances that the resource needs to travel prior to treatment at the plant and distribution or from the deep wells that water needs to be pumped from. Transporting the water from a remote source also involves capital costs for creating appropriate infrastructure. Smaller utilities use more electricity and pay more per unit of water produced than do medium and large utilities, due to economies of scale. Nearly all of the energy consumed is electricity, about 80% of which is used by motors for pumping and transporting [12].

2.2. Energy for desalination (thermal and membrane desalination)

Desalination of saline water sources has been sought as an alternative to fill the gap between demands and supply for freshwater in many areas severely challenged by the scarcity of freshwater sources. Desalination is a nonconventional water treatment technology applied to recover freshwater from surface and ground waters that have high dissolved solids (TDS) concentrations. In the early 1950s, thermal desalting technologies such as multi-stage flash (MSF) desalination, multi-effect evaporation desalination (MED) and mechanical vapor compression (MVC) were commercialized, which consumed enormous amounts of thermal energy with specific energy requirements between 30 and 120 kW h$_{th}$/m^3 (10.5 and 42 kW h$_e$/m^3) [13]. With the advent of reverse osmosis (RO) technology and remarkable improvements in the membrane performance and associated reductions in energy consumption, RO technology has increased its visibility compared to thermal desalination technologies due to its much less specific energy consumption between 3.5 and 5 kW h$_e$/m^3 [10]. Desalination by RO process is recognized as a feasible option particularly in areas where transportation cost of freshwater and high living standards override the negative impacts of desalination such as energy- and cost- intensiveness. For instance, a recent evaluation for the city of Los Angeles, California concluded that freshwater supply based on RO desalination technology requires the same amount of energy (2.8 kW h/m^3) that would be required to transport surface water (2–3 kW h/m^3) from the delta region or from other surface water sources [10].

2.3. Energy for bottled water production

Bottled water market has seen an unprecedented growth all over the world with rapid industrialization. For example, 200 billion liters of bottled water was sold globally in 2007 [14]. Bottled water supply involves a very large energy footprint, for instance, energy is required to make, package, transport, cool, use and recycle bottled water and its packaging material. The total energy required for all these steps varies largely for various scenarios. Plastic bottles manufacturing requires 4.0 MJ$_{th}$/L (0.39 kW h$_e$/L) of energy with water treatment at bottle plant between 0.0001–0.02 MJ$_{th}$/L (0.002 kW h$_e$/L), filing operations up to 0.01 MJ$_{th}$/L (0.001 kW h$_e$/L, transportation between 1.4 and 5.8 MJ$_{th}$/L (0.14–0.56 kW h$_e$/L) and cooling between 0.2 (0.019 kW h$_e$/L) and 0.4 MJ$_{th}$/L (0.039 kW h$_e$/L) respectively. In comparison, producing tap water typically requires about than 0.005 MJ/L for treatment and distribution [14,15].

2.4. Energy for wastewater treatment

Water and wastewater treatment plants account for 3 to 4% (56 billion kW of electricity) of total nationwide (U.S.) electricity utilization which in some communities measures anywhere between 20 and 40% of total energy consumption. This energy consumption is in similar range for other developed countries. Apart from the greenhouse gas emissions related to the energy consumption, they also emit 45 million tons of carbon dioxide annually in U.S. (this is not usually counted as GHG emission) due to organic waste degradation [16]. In addition, water and wastewater systems representing a second major cost item for utilities with expenditures nearly $4 billion a year. It is also estimated that over the next twenty years an additional $45 billion will need to be expended to maintain and improve the infrastructure [17]. Reducing energy consumption for wastewater treatment will avoid environmental degradation involved in energy production. The energy autarky of the wastewater treatment systems is important from many perspectives such as elimination of air

Table 1
Benefits of improving energy efficiency in water and wastewater facilities [91–111].

Advantage	Description	Example
Reduce air pollution and GHG emissions	GHG emissions and criteria air pollutants can be significantly reduced by decreasing consumption of fossil fuel-based energy. Fossil fuel combustion for electricity generation accounts for approximately 40% of the nation's emissions of carbon dioxide (CO_2), a principal GHG. It also accounts for 67% and 23% of the nation's sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions, respectively. These pollutants can lead to smog, acid rain, and airborne particulate matter that can cause respiratory problems for many people	The Green Bay, Wisconsin Metropolitan Sewerage District has two treatment plants that together serve more than 217,000 residents. One of the treatment plants installed new energy-efficient blowers in its first-stage aeration system, reducing electricity consumption by 50% and saving 2144,000 kW h/year – enough energy to power 126 homes – and avoiding nearly 1,480 metric tons of CO_2 equivalent, roughly the amount emitted annually by 290 cars
Reduce energy costs	Local governments can achieve significant cost savings by increasing the efficiency of the pumps and aeration equipment at a water or wastewater treatment plant. A 10% reduction in the energy use of U. S. drinking water and waste-water systems would collectively save approximately $400 million and 5 billion kW h annually. other approaches to reduce energy costs are shifting energy use away from peak demand times to times when electricity is cheaper or (for wastewater plants) using CHP systems to generate their own electricity and heat from biogas	Waste Water Treatment Plant in Albert Lea, Minnesota developed a 120-kW microturbine CHP system, which saves the plant about $100,000 in annual energy costs. About 70% of the savings resulted from reduced electricity and fuel purchases, and the remainder from reduced maintenance costs. The installation of the CHP system raised awareness at the plant about energy use in general, and led to a number of other energy efficiency improvements and additional cost savings
Support economic growth through job creation and market development	The energy efficiency services sector accounted for an estimated 830,000 jobs in 2010, and the number of jobs was growing by 3% annually. Most of these jobs are performed locally by workers from relatively small local companies. Furthermore, facilities that reduce their energy costs through efficiency upgrades can spend those savings elsewhere, often contributing to the local economy	In an initiative led by the city's current mayor when he was at alderman, a group of residents and city staff led an initiative in 2008 to develop a plan to make the City of Franklin, Tennessee, more environmentally sustainable. This group created the city's 2009 Sustainability Community Action Plan, which called for reductions in energy use and GHG emissions, and directed
Demonstrate leadership	Investing in energy efficiency epitomizes responsible government stewardship of tax dollars and sets an example for others to follow. By implementing energy efficiency and water efficiency projects at water and wastewater facilities, a local government can demonstrate not only the dollars saved, but the environmental benefits that are obtained from reducing energy and water use. Installing energy-efficient products (e.g., more efficient pumps), water-efficient products (e.g., WaterSense products), and renewable energy technologies (e.g., solar panels) may facilitate broader adoption of these technologies and strategies by the private sector—particularly when communities publicize the economic and environmental benefits of their actions	Franklin's utilities to become more involved in energy efficiency audits. As part of its effort to meet the action plan's energy goals, Franklin participated in the Tennessee Water and Wastewater Utilities Partnership, co-sponsored by EPA Region 4. The partnership helped Franklin's water department identify and implement opportunities to reduce energy costs by more than $194,000 per year – a 13% reduction – through changes in operations and installing energy-efficient lighting. The improvements have avoided more than 1280 metric tons of GHG emissions, equivalent to the annual emissions from powering 125 homes
Improve energy and water security	Improving energy efficiency at a water or wastewater treatment facility reduces electricity demand, avoiding the risk of brownouts or blackouts during high energy demand periods and helping to avoid the need to build new power plants. Water efficiency strategies reduce the risk of water shortages, helping to ensure a reliable and continuous water supply	The East Bay Municipal Utility District (EBMUD), which provides drinking water to 1.3 million customers and handles wastewater for 650,000 customers in the San Francisco Bay Area, transformed itself from an energy consumer to a net energy producer. By 2008 the district had brought its GHG emissions back to their 2000 level and then reduced them by an additional 24% the following year, all while insulating itself from energy price fluctuations and supply uncertainties. EMBUD started its energy transformation by cutting its energy use requirements to the point where its facilities now use 82% less energy than the California average for delivering 1 million gallons of drinking water from source to tap. It accomplished these improvements through design features, such as delivering drinking water via downhill pipes rather than using electric pumps, and through energy efficiency upgrades such as installing microturbine CHP units. EBMUD's remaining energy needs are met by renewable energy systems, including hydropower, solar, and biogas. Excess power produced by the renewables provides a source of income through sales of electricity into the grid
Extend the life of infrastructure/equipment	Energy-efficient equipment often has a longer service life and requires less maintenance than older, less efficient technologies. Efforts to improve water efficiency or promote water conservation can also extend the life of existing infrastructure due to lower demand, and can avoid the need for costly future expansions	Millbrae, California implemented a program to divert inedible kitchen grease from the city's wastewater system, where it could clog sewer lines and cause releases of raw sewage into the environment, posing risks to public health. Waste haulers collect the grease daily from area restaurants and deliver it to the
Protect public health	Improvements in energy efficiency at water and wastewater facilities can reduce air and water pollution from the power plants that supply electricity to those facilities, resulting in cleaner air and human health benefits Equipment upgrades may also allow facilities to increase their capacity for treating water or wastewater or improve the performance of treatment processes, reducing the potential impacts of sea level rise, treatment failures, and risk of waterborne illness	wastewater treatment facility, where it is processed in digester tanks to create biogas. Before the program was implemented, the grease ended up in area landfills where its decomposition produced methane emissions. The treatment plants digester system produces enough biogas to generate about 1.7 million kW h of electricity annually, meeting roughly 80% of the plant's power needs
Country	**Energy/water efficiency measure**	**Achieved benefits (savings)**
Australia	Applying new coating to pump casing volute and impeller to reduce water friction loss	20%—energy cost
Australia	Active leakage control through pressure management, combined with water main renewal and flow meter upgrade	45%—water
Australia		Reduced energy intensity

Table 1 (*continued*)

Advantage	Description	Example
	Development of a preventative maintenance strategy (retrofitting a flap valve and ongoing audit of wastewater pumping stations' constructed overflows) for future inspections	
Austria	All existing about 950 WWTPs with a total of about 20 million design PE were invited to take part in a benchmarking process, which annually compares individual cost figures with the overall national performance. Participation is voluntary and any individual data remains unknown to all other participants. Thus a participating WWTP is informed just about its own data in comparison to the overall benchmarks, medians, etc. The first such benchmarks were developed for the year 1999, the latest publicly available data refers to the year 2004	Within that 5-year period the relative contribution of energy cost to the benchmark has shrunk by about 30%, and thus constitutes the single most relevant factor for overall reduction of the operation cost benchmark. Consequently, the median of energy cost for large WWTPs has fallen to about 1,0 EUR/PE/a (euros per population equivalent per annum), with the best performing WWTPs already approaching zero energy cost
Belgium	VSD for 11 well pumps	15%—electricity
Brazil	VSDs for raw water extraction pumps and clean water distribution pumps at a Brazilian water treatment plant	33%—electricity 19%—kW demand 44%—energy bill
France	Using sludge and other organic waste as fuel in the process to improve their overall energy balance	80–88%—energy (for thermal drying of sewage sludge)
Germany	344 WWTPs in North Rhine Westphalia (NRW) have undergone energy analysis. The findings indicate that energy cost can be reduced by an even higher margin than in Switzerland that is by an average of 50%	Extrapolation of findings in NRW leads to an overall savings potential in Germany equaling 3 to 4 billion EUR over 15 years
Mexico	Optimization of distribution network using hydraulic modeling to regulate water pressure and flows; network sectorization, leakage detection and repairs; new pumps and motors,	27%—electricity Reduced leakage Increased revenue
Netherlands	Installation of a hydraulic connection of water pumping stations	19%—electricity
Singapore	Designing and operating the aerobic sludge retention time (SRT) and hydraulic retention time (HRT) based on the conditions in warm climates	46%—electricity
Singapore	One-stage mesophilic anaerobic digestion with dual fuel engine CHP	About 15% reduction in purchased power
South Africa	Active leakage control by investing in new pressure management facility to reduce high physical losses	30%—water
South Africa	Retrofitting and replacement of plumbing fixtures like cisterns, taps, pipes and valve,	31%—electricity
Switzerland	Two thirds of all WWTPs in Switzerland have already undergone energy analysis. Because of that, energy cost has been reduced by an astounding average of 38% so far. 2/3 of this cost reduction is due to increased electricity production from biogas, 1/3 is due to "real" savings.	Major efficiency increases were realized in the biological stage and with improved energy management. Current savings amount to 8 million EUR/a. Over an investment life-span of 15 years this equals 120 million EUR
UK	Variable speed pump control changes – reduction in operational frequency on VSD and pumping rate	12%—electricity
UK	Using raw water quality monitoring to determine if DAF plant is required to treat water to outlet quality	21.4%—electricity
UK	Increasing CHP generation with new 320 kW CHP engine to reinforce an existing CHP generation comprising 104 kW and 165 kW engines	Reduced power purchase
USA	Adding VFD Control of oxidation ditch rotors using 4–20 mA signal from optical dissolved oxygen (DO) probes	13%—electricity 39%—kW demand 22%—cost
USA	Single-stage centrifugal blowers with inlet guide vanes and variable outlet vanes, and of air control valves	30%—electricity
USA	Installation of a 502 kW DC ground-mounted, dual-array PV systems in 2005 and a 99 kW solar PV system in 2008,	Reduced power purchase
USA	Cogenerating electricity and thermal energy onsite from waste methane; installing high efficiency influent and effluent pumps, high efficiency motors, and VFDs; discontinuing second-stage activated sludge mixing; adding plastic balls to prevent heat and evaporation losses in oxygen production vaporizer pit; and replacing two small compressors at the pure oxygen plant with 1 large unit	Reduced power purchase

pollution and greenhouse gas emissions, improving economics, enhancing energy and water security, extending the life of the infrastructure and protecting public health and environment. Table 1 shows the benefits of improving energy efficiency of water and wastewater treatment systems with examples from the utilities in the United States and around the world.

A typical domestic wastewater treatment plant with aerobic activated sludge treatment and anaerobic sludge digestion technology consumes 0.6 kW h of energy per m^3 of wastewater treated, about 50% (even higher) of which is for electrical energy to supply air for the aeration basins [6]. Wastewater treatment by lagoons, trickling filters, activated sludge and advanced wastewater treatment require 0.09–0.29, 0.18–0.42, 0.33–0.60, and 0.31–0.40 kW h/m^3 respectively [18]. Biogas (CH_4) produced from anaerobic digestion (AD) could satisfy 25–50% of the energy requirements for aerobic activated sludge treatment and other plant modifications may further reduce energy needs considerably. However, if more of the energy potential in wastewater were captured for use and even less were used for wastewater treatment, then, wastewater treatment might become a net energy producer rather than a consumer [19]. Fig. 2b shows the low, median and high energy consumption values for wastewater treatment plants varying in size. Energy requirements decrease with the plant size, the trend being similar for low, medium and high ranges. Treatment energy requirements generally decline as facility size increases; even within a size category, variation in energy requirements is large and is driven by other factors, including the type of filtration and source water quality. Facilities using pressure filtration and oxidation are likely at the higher end of the range, whereas facilities using direct or sand filtration are likely at the lower end of the range. For large-scale plants, large variations between the low and high values can be observed due to an advanced treatment train for biological nutrient removal or lack of an energy recovery unit such as an anaerobic digester [20].

Fig. 3 shows the complete water supply and wastewater treatment cycle for a 10 MGD plant capacity with most commonly used unit operations and processes [21]. The surface water treatment processes include traditional treatment train consisting of raw water collection, rapid mixing, flocculation, sedimentation steps followed by filtration and disinfection before distribution to the end users. The conventional wastewater treatment by activated sludge process involves primary physical separation followed by secondary biological treatment and discharge to the surface receiving water bodies. For drinking water treatment, the major component of energy consumption is distribution and for wastewater treatment, the aeration system in the activated sludge process. The details of the energy consumption patterns and recovery options are presented in the following sections.

3. Paradigm shift (wastewater treatment)

The goals of the wastewater treatment plants are currently evolving from water purification (sanitation) and environmental protection towards the additional goals of making this through a more environmental-friendly manner by recovering the valuable resources such as nutrients and water, and by recovering chemical and thermal energy and by improving the energy efficiency of the overall process. Conventional activated sludge processes are being recognized as energy intensive and chemical consuming with excess sludge disposal issues. Even more energy and chemical intensive are the biological nutrient removal processes namely sequential nitrification and denitrification process in practice today. The paradigm shift in the wastewater treatment practice should be to design treatment processes that are energy-positive or at the least energy-neutral along with enhanced water, energy, and nutrient recovery which are valuable resources. How this can be achieved depends on various factors subject to the wastewater quality, quantity and the seasonal variability, and the operational strategy of the wastewater treatment plant and overall economics. The new goals for the wastewater treatment plant design and operations should: (a) achieve existing public health and environmental goals, (b) maximize energy and water recovery from wastewater, and (c) preserve or recover nutrients for reuse [22].

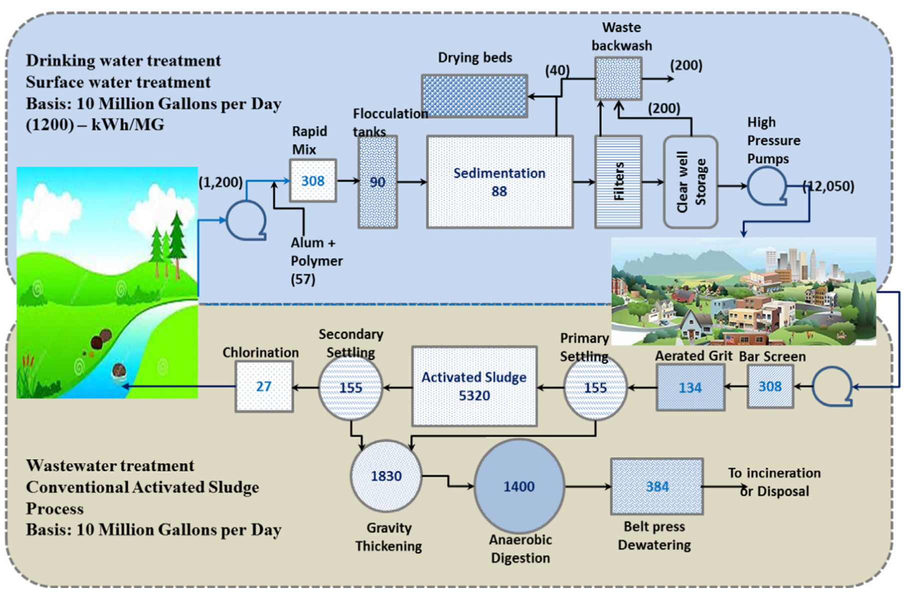

Fig. 3. Energy requirements for conventional water and wastewater treatment operations and processes.

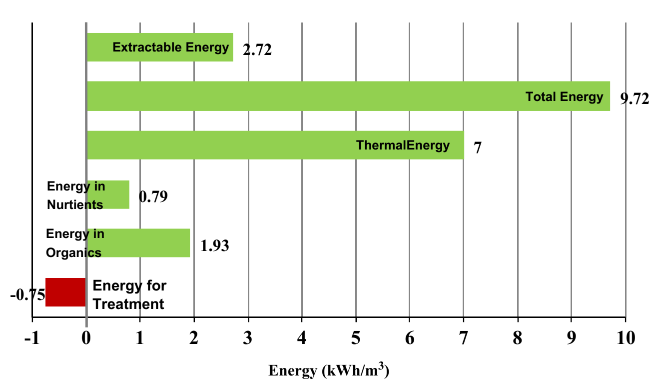

Fig. 4. Available energy forms in wastewater sources.

Fig. 4 shows the different forms and quantities of energy that can be recovered from wastewater sources which include thermal energy in the water and chemical energy present in the form of organics and nutrients. Additionally, hydraulic (kinetic and potential) energy may be available for plants that receive sewage from a higher elevation or discharge the effluent to a lower point. Thermal energy can be harvested using a heat-pump and this energy is available through sensible heat of the wastewater. Thermal energy as much as 41,900 MJ/m^3 of wastewater is possible for every 10 °C temperature difference. The chemical energy ranges between 12 and 15 MJ/kg of COD (organics) and between 27.4 and 29.4 MJ/kg of suspended solids (primary and secondary sludge together) [23]. It was estimated that wastewater contains 9.3 times the energy required to treat it [24]. McCarty et al. [6] reported that energy content levels as shown in Fig. 4. By looking at the energy consumption levels, the recoverable energy in the wastewater is between 3.6 (with energy recovery from organics and nutrients) and 13 (including heat recovery) times higher than the actual energy required for treating. Also, the economic value of potential product recovered in the forms of water, nitrogen, methane, organic fertilizer and phosphorous per unit of wastewater is about $0.47 [25]. Water itself is the major and most valuable resource among these forms. Therefore, wastewater is now being recognized as a valuable resource and is named "sewage" and the wastewater treatment plants are termed as "water resource recovery facilities (WRRF)". Hydraulic energy is mainly available through kinetic and potential energy forms. Potential energy is the energy due to the water elevation and is calculated by mass × acceleration due to gravity × head = 9.8 kJ/m^3 per m of head for water. Kinetic energy, or the energy due to the momentum of the water, is calculated as $0.5 \times mv^2 = 0.18$ kJ/m^3 for a water velocity of 0.6 m/s (2 ft/s). Most of the wastewater plants are located on the low elevation and very close to the river body, thus the hydraulic head will not be so significant and will provide a small amount of energy.

4. Opportunities for energy recovery and savings in wastewater treatment

4.1. Energy conservation in water treatment

Water treatment processes do not possess the energy generation potential but can be designed to operate by gravitational energy available from the elevation difference to reduce energy consumption. If the source water is available at a higher elevation, the design of these systems is possible with about 1.5 m elevation drop. The treatment process involves the same process unit operations and processes except that the pumps and the electricity requirements for their operation are eliminated or significantly reduced. Such water treatment plants are being designed especially for serving populations in rural communities and developing countries with no or limited access to electricity. The electricity costs can count up to 20% of the freshwater costs. Together with electricity elimination for process operation and other localized process equipment procurement and solutions, Aquaclara® is able to reduce the freshwater costs by 50% of that required for traditional surface water treatment plants [26]. Alternatively, the same elevation difference can be utilized to produce electricity by use of mechanical turbines suitable for desalination and other water purification process applications. These strategies are suitable for locations with low or intermittent access to the local electricity sources. In case of wastewater treatment, numerous opportunities exist for energy conservation, efficiency and recovery making the overall process net energy-positive or energy-neutral. The following sections discuss a few potential energy recovery options and energy efficiency schemes applicable to wastewater treatment.

4.2. Hydraulic energy recovery

Hydraulic energy recovery from effluent drops was undertaken at a wastewater treatment plant in Vienna, Austria. The wastewater (AWTP) discharges 560,000 m^3/d (148 MGD) into Danube river with elevation drop to Danube River from plant outfall of 5 m (16.5 ft drop) between headworks and Danube River. The electricity requirements for the plant operation are 175,000 kW h/d (63.8 Million kW h annually). The vertical axis turbine produces 1.5 Million kW h per year used on site in treatment plant's grid (2.6% of plant use) [27]. The Clark County wastewater treatment plant in Nevada, USA treats about 150 MGD wastewater daily. The treated effluent from this county to Lake Mead is expected to increase to 400 MGD by 2050. Approximately, 400 ft of effluent drop is available along the conveyance length of 72,000 ft (overall slope, ~0.56%) to the discharge point. A 16 MW hydroelectric generating station consists of two 8.25 MW Francis type turbines which produce over 85 Million kW h per year. The annual pumping energy required is about 4 Million kW h, the remaining energy supplied to nearby grid. The net present value of the system is $60/MW h ($0.06/kW h) [28].

4.3. Heat recovery

The US Department of Energy (DOE) estimates that about 235 billion kW h of thermal energy in the form of waste hot water is discarded into drains in a year and only a tenth of that energy is required to treat the wastewater (18–24 × 10^3 million kW h/yr) in the treatment plants. The waste heat in the sewage is about 400 Billion kW h for the North America including Canada [29]. In Vancouver Canada, the False Creek Energy Centre integrated with a municipal wastewater pumping station recovers heat from untreated urban wastewater. Wastewater that flows into the pump station is diverted to a traveling-screen filter that removes solids before the flow is sent to a heat pump. Similar to a geothermal application, heat pumps are used to transfer the heat energy from the wastewater to a hot-water distribution system. Heat pumps use a refrigerant evaporation-compression cycle to transfer heat from a low-grade source (wastewater) to a higher-grade source (hot water). After heat recovery from the wastewater, the wastewater and filtered solids are recombined and pumped to the Iona Island Wastewater Treatment Plant outside of the municipal boundary. The heat-pump system in this application provides a higher level of energy output than initially planned—3.5 MW versus the planned 2.7 MW [30].

Prior to considering the extraction of waste heat from the sewage, the economics and expected benefits need to be questioned. To implement a successful project, the following should be considered: extractable energy (quantity) available in wastewater; expected best use for the extracted heat, the types of systems and infrastructure required and the cost to implement and the financial package. Additionally, the impact of heat extraction on the biological treatment of wastewater needs serious consideration since the microorganisms working in the downstream sewage treatment systems are temperature sensitive.

4.4. Combined heat and power (CHP) systems

The working principle behind the combined heat and power systems is that a single fuel form is converted into electricity and heat where the waste heat from electricity generation is recovered for productive use in the plants [31]. Anaerobic digestion system can be coupled with the CHP system for effective use of this waste heat.

The biogas generated by the anaerobic digestion (AD) system provides the necessary fuel for the CHP system so that both systems can benefit from each other. There are five types of equipment used in CHP systems which include gas turbines, micro-turbines, steam turbines, reciprocating engines and fuel cells. Gas turbines are used for large-scale applications with capacities between 500 kW and 250 MW while micro-turbines are installed in applications with capacities between 30 kW and 250 kW. Steam turbines produce an intermediate product (steam) between fuel source and electricity generation with a wide range of applications between 50 kW and 250 MW [32]. Reciprocating internal combustion engines are used in small-scale stationary power generation systems with ranges between 10 kW and 5 MW. Fuel cells are relatively a new CHP technology with high process efficiency and low emissions but suffer from high capital costs and durability issues. Current sizes of applications are between 50 W and 2 MW. The New York Authority was the first to use a fuel cell with AD gas successfully in 1997. Despite several installations in the USA, these require additional research and expertise for their wide application in the industry and in conjunction with AD biogas.

4.5. Biogas generation (anaerobic digestion, AD)

Verstraete et al. [33] reported an energy balance comparison between the conventional activated sludge (CAS) treatment and anaerobic digestion process. The CAS process requires 25 kW h of electrical energy per capita per year whereas the new design with anaerobic digestion produced a net energy of 5 kW h of electrical energy. This means that by not implementing novel treatment units and processes about a 30 kW h per capita per year equivalent electrical energy losses can be realized. Anaerobic digestion has been applied for over 20 years for domestic wastewater treatment, mainly utilizing the upflow anaerobic sludge blanket technology. However, poor effluent quality (> 100 mgCOD/L), effluent dissolved methane (a potent greenhouse gas), and negligible nutrient removal, have restricted its application in countries where strict effluent discharge limits apply (e.g., $N < 10$ mg N/L) [22]. As a rule of thumb, anaerobic digestion produces about 35 m^3 of gas per day per person, which has a typical heating value of approximately 6.2 kW h/m^3 [34] with water vapor and small amounts of siloxanes and hydrogen sulfide as impurities, which must be removed to prevent damage to the power generation equipment in electricity production. The methane content of biogas is the usable portion of the gas and determines its calorific value. Methane has a heat value of 100 BTU/ft^3 and with electrical conversion efficiency of 33%, 0.063 kW h/ft^3 (2.24 kW h/m^3) of electricity can be produced. Biogas is utilized as fuel in vehicles in some European countries. It requires upgrading prior to use as vehicle fuel and goes through a series of cleaning steps (compression, CO_2 and H_2S removal by water absorption followed by adsorption drying) to improve the quality to > 97% methane purity, 2.5% carbon dioxide and the remaining H_2S. Some European countries have advanced in this technology to utilize biogas. Sweden leads the world in biogas utilization, using 55% of the 1.2 TW h produced in 2006 for heat, 19% as vehicle fuel, 8% for electricity and 4% for biogas injection to the gas grid [35]. Germany has set a goal to replace 6% of its natural gas demand by biomethane in 2020, rising to 10% in 2030. In order to achieve this, the government already changed the gas-grid connection ordinance in March 2008.

Biogas recovery potential depends on the plant size and the economics. The Environmental Protection Agency (EPA) Combined Heat and Power Partnership estimates that approximately 491 kW h of electricity can be produced with a microturbine and 525 kW h of electricity can be produced with an internal combustion engine for each million gallons of wastewater treated at a plant with anaerobic digestion [34]. Small plants with capacity less than 5 MGD will not be able to implement the anaerobic digestion system since the economics of the process are not justified for the amount of energy that could be recovered through biogas generation. Fig. 5 shows the energy balances on the wastewater treatment plants for four different capacities (1, 5, 10, and 50 MGD) using a conventional activated sludge treatment system. The small plants do not have an anaerobic digester but the larger plants (10 and 50 MGD) have it in place. The energy balance on the 10 MGD plant shows that 33% of the total energy can be recovered via biogas generation whereas the 50 MGD plant can recover up to 41%. It indicates the effect of plant size on the economics and recoverable energy of the AD system. Biogas production can be enhanced by making the secondary sludge more digestible by pretreatment [36] Cell lysis by mechanical processes such as sonication, pulsed electric fields, heat and pressure (CAMBI), and heat and chemicals (micro-sludge). Co-digestion of other organic waste such as kitchen waste, fats, oils and greases and even other biological sludge such as algal biomass can improve the biogas quantity significantly [37].

With conventional, independently operated systems, biofuel production from algae requires significant amounts of nitrogen, phosphorus, carbon dioxide, and water, all of which require energy directly and indirectly; in addition, the WWTPs require significant energy inputs for treatment of the waste streams. However, an integrated configuration may reduce the energy demands because outputs from one system can serve as the inputs for the other. Consequently, the energy balances for the integrated system can significantly outperform those from the isolated system [38]. Since anaerobic digestion of the biosolids alone cannot make the wastewater treatment self-sustainable, a few studies investigated integrating the algal biomass cultivation using wastewater so that the biomass can be utilized to produce biogas to off-set the energy requirements in the process. An energy return on investment (EROI) analysis performed on an integrated process showed that energy generation from co-digestion of algal biomass and the savings in the wastewater treatment is 2 times the energy consumed for biomass cultivation, harvesting and processing (AD) and the reduced energy generation from secondary sludge (energy input). Digestion from wastewater sludge alone had an EROI of 0.38 without algal biomass cultivation. The integrated configuration was evaluated in three different scenarios based on utilization of CO_2 available locally and the land requirements for algal biomass cultivation [39].

Since microalgal biomass has a complex cell wall structure and strength, the digestion of this biomass to produce biogas is not similar or easy compared to the wastewater sludge. To increase the digestible nature of the algal biomass and thus the biogas production, thermal pretreatment at relatively low temperatures of $75-95$ °C was considered. Energy balances based on lab-scale reactors performance at 20 days HRT, shifted from neutral to positive (energy gain around 2.7 GJ/d) after thermal pretreatment. In contrast with electricity consuming pretreatment methods, such as microwave irradiation, thermal pretreatment of microalgae seems to be scalable [40]. Apart from the wastewater treatment plants, the methane potential from landfill material, animal manure, and industrial, institutional, and commercial organic waste in the United States is estimated at about 7.9 million tonnes per year, which is equal to about 420 billion cubic feet or 431 trillion British thermal (BTU) units. This amount could displace about 5% of current natural gas consumption in the electric power sector and 56% of natural gas consumption in the transportation sector [41]. While this resource potential appears small and easy to overlook given the abundance of relatively inexpensive natural gas, it presents an opportunity for greenhouse gas mitigation (methane is 21 times more potent than carbon dioxide) and production of renewable energy fuel [42].

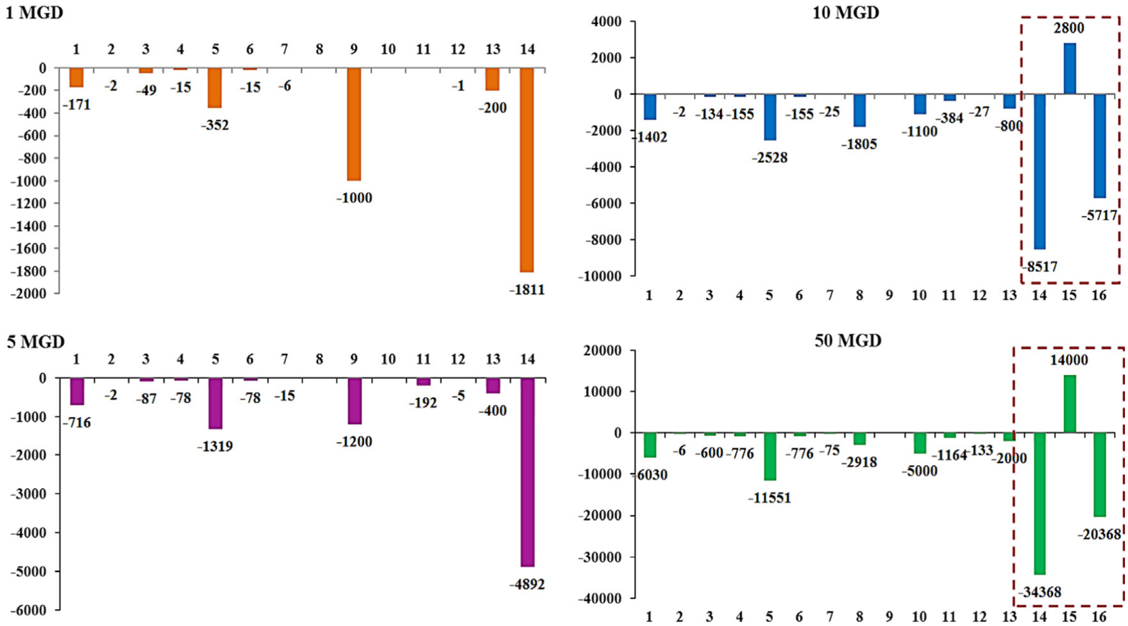

Fig. 5. Energy consumption and energy recovery potential in wastewater treatment process. (1—wastewater pumping; 2—screens; 3—aerated grit removal; 4—primary clarifiers; 5—trickling filters; 6—secondary clarifiers; 7—gravity thickening; 8—dissolved air floatation; 9—aerobic digestion; 10—anaerobic digestion; 11—belt filter press; 12—chlorination; 13—lighting and buildings; 14—total; 15—recovery; 16—net).

4.6. Algae growth for biofuels

Pittman et al. reported the potential for various wastewater sources including domestic wastewater as algal cultivation medium for biofuels [43]. Details can be found elsewhere. A second order EROI analysis on the WWTP and algal biofuels production process (operating in isolation from each other) was found to be 0.37 and 0.42, respectively indicating that in conventional operation, both systems are operating as energy sinks [44]. However, when the two operations are combined, energy inputs can be reduced significantly. Consequently, the integrated system can outperform the isolated system, yielding a second-order energy return on investment of 1.44. Combining these systems transforms two energy sinks to a collective (second-order) energy source. However, these results did not include capital, labor, and other required expenses, suggesting that profitable deployment will be challenging. This mutually beneficial scenario corresponds to an energy savings (or production) of roughly 5.5 kJ/L processed water for algal biofuel production (equivalent to 5.0 kJ/L wastewater). In the independent case, wastewater required 6.0 kJ/L processed water; therefore, this energy savings and production represents an offset of nearly the entire operating energy cost of wastewater treatment. Applying this result for all the wastewater processed in the United States (4.5×10^{13} L wastewater per year [44,45] corresponds to a net energy effect of roughly 220 PJ/yr (220×10^{15} J/yr). While this represents less than 1% of the United States' annual energy consumption, it is still significant enough to be relevant [38].

4.7. Anammox process (novel configurations)

About 40–50% of the total energy consumption in the municipal WWTPs can be reduced or met by biogas utilization. Additionally, net electrical consumption can be more than halved with the introduction of separate sludge liquid treatment [46]. An activated sludge WWTP in Strass, Austria has achieved energy self-sufficiency by implementing a high rate aerobic process, anammox treatment of nutrient rich side streams, and on-site electricity generation from biogas generated by solids digestion. The aerobic BNR process, in which 31% of the influent COD and 80% of the N is removed, accounted for 45% of energy consumption at the plant. Recently, Shoener et al. [5] evaluated the energetic potential of replacing the existing aerobic processes with anaerobic and phototrophic processes for wastewater treatment. They reported an increase in total plant biogas production by 39% and energy recovery from COD up to 41%. This study concluded that combined anaerobic and phototrophic processes could reduce energy demand and achieve energy recovery and production on the order of 5.0–9.2 kW h/m^3 well above the whole-plant energy demand of conventional WWTPs (0.3–0.6 kW h/m^3).

An innovative DEMON® (DEamMONification) sidestream process was first operated in a full-scale installation of any form of anammox sidestream treatment in North America. Deammonification, partial nitritation by ammonia oxidizing bacteria (AOB) combined with anaerobic ammonium oxidation (ANAMMOX) provides up to 70–90% total nitrogen removal with a 65% reduction in aeration energy, a 100% reduction in supplemental carbon, and an approximate 50% reduction in alkalinity requirements as compared to traditional nitrification-denitrification [47,48]. The DEMON® process is one of several available forms of single-step (in the same tank) partial nitritation-anammox designed for centrate treatment from anaerobically digested biosolids and operated as a sequencing batch reactor (SBR). While this process had been applied at approximately 30 plants in Europe, it had not been implemented elsewhere in a full scale application, primarily because of the requirements for seeding this process using biomass imported from operating facilities in Europe [49].

4.8. Microbial fuel cells

In conventional wastewater treatment systems including activated sludge (or biological treatment process) followed by an aerobic digester, majority of the energy present in the organic compounds is converted to carbon dioxide without much energy generation but with a higher sludge yield. However, if the carbon energy source present in the wastewater can be diverted to novel anaerobic processes like microbial fuel cells (MFCs), energy recovery potential can be further enhanced [18]. MFCs can be integrated with the wastewater treatment systems in a variety of configurations. MFCs

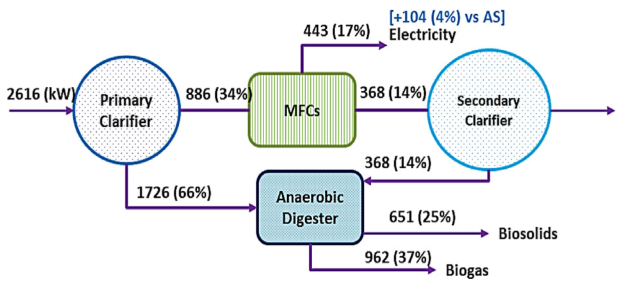

Fig. 6. Possible energy recovery options with MFC and AD integration.

can be potentially combined with a membrane bioreactor (MBR) process or immersed in aerobic or anaerobic tanks (depends on the existing wastewater treatment scheme) or even can be designed to be standalone after anaerobic digestion process to utilize its effluent. Logan presented an energy balance on the MFC based wastewater treatment in that the MBR process could not be a self-sustaining process based on the energy content of the wastewater since the MBR system requires 8250 kW per m^3/s of wastewater flow. An energy balance on the MFC integrated (shown in Fig. 6) with wastewater treatment and AD system could produce 17% of energy in the form of electricity and 37% in the form of biogas. Apart from that the process also saves a 104 kW/MGD of wastewater treated increasing the overall energy recovery up to 58% [18]. In another study, Logan [50] provided a brief economic analysis on the MFC based electricity production based on a population of 100,000 people generating 16.4×10^6 L of wastewater with 300 mg/L of BOD. If all the available energy can be captured by MFCs, this process can produce an estimated 0.5 MW of electricity adequate for 330 homes. The annual revenues will be between 1 and 5 millions US Dollars for electricity prices between $0.05/kW h and $0.44/kW h depending on the location. This analysis indicates that economic incentive to develop and adopt electricity production with wastewater treatment by MFCs will vary [50]. Recent developments have shown a magnitude of order increase in the power production rates in MFCs indicating their potential to become standalone energy-positive wastewater treatment systems [18].

4.9. Microbial desalination cells (MDCs)

A novel approach to integrate the wastewater treatment and desalination processes with concurrent electricity production resulted in microbial desalination cells (MDCs) technology [51]. Microbial desalination cells are a recent innovation that allows for simultaneous wastewater treatment and desalination due to inherent ionic transfer between the anode and cathode chambers. MDCs similar to MFCs can be applied to treat a variety of impaired waters such as agricultural, industrial, dairy and farm wastewaters, groundwater with high nitrogen concentrations (nitrate and nitrites) [52] or hard waters (with high hardness, Ca^{2+} and Mg^{2+}) in the desalination chambers [53]. For any bio-electrochemical system, a strong electron acceptor is essential for continued operation. This electron acceptor should be economically viable, non-toxic and derived from renewable sources. Oxygen is a cheap and strong electron acceptor, which can be supplied from air. Alternatively, photosynthetic systems can be integrated in the cathode chamber to provide in-situ electron acceptors (oxygen) [1,54,55]. They also provide for additional nutrient removal from the wastewater. In MDCs, membranes play a significant role, therefore, membrane fouling due to chemical and biological factors becomes an important issue similar to other membrane based desalination systems [7]. MDCs produce less power compared to MFCs due to the internal resistances in the system, which is a major research focus currently.

4.10. Energy efficiency programs in USA and around the world

Fig. 7 shows the energy distribution patterns in water and wastewater treatment plant operations. Water distribution in the water treatment systems takes up a large portion of energy expenditure. It varies between 50% and 85% form large to small systems respectively [56]. Raw water pumping and in-plant pumping also account for significant energy consumption. Similarly in wastewater treatment plants, the aeration equipment consume anywhere between 50% and 75% of the total energy consumption from large to small plants respectively. Anaerobic digestion and wastewater consumption are the next two major energy-consuming steps. This also indicates potential opportunities for many energy recovery and conservation schemes and for improving economic and environmental benefits.

Energy efficiency and improvement programs can play a critical role in achieving the energy autarky of the water and wastewater treatment systems. The communities need to look into a systematic portfolio wide approach to consider all the facilities within boundaries. Similarly, determining goals for energy improvements for the water and wastewater projects at the beginning of the projects is important so that the design can be modified accordingly. These goals can be ambitious but realistic and can be both quantitative e.g., reduce overall energy use by 25% in three years) or qualitative (e.g., implement a community education program, setting an example for other facilities). Facilities need to develop a mix of quantitative and qualitative goals to cover a range of quantifiable and non-quantifiable actions. Whenever possible, these goals can be developed as part of the facility's ongoing planning processes. Table 1 provides a long list of energy efficiency programs undertaken at various locations around the world and the achieved energy, economic and environmental benefits associated with the process improvement. For example, in secondary wastewater treatment about 15 to 38% energy savings can be achieved with aeration system optimization, 4 to 15% of energy savings can be achieved by addition of pre-anoxic zones for a biological nutrient removal, and flexible sequencing of aeration basins can save 8 to 22% [57]. Similarly, for anaerobic digester biogas systems, 13 to 57% of energy gap can be reduced (in other words, increasing energy generation potential) by combining with boilers, 11 to 61% with cogen engines, 5 to 38% with microturbines, 7 to 46% with turbines, and 6 to 42% with fuel cells. As discussed before, co-digestion may reduce the energy gap between 2 and 128%. For communities that process wastewater in small quantities and of low strength (low BOD) may consider decentralized natural and onsite treatment processes that are low-tech, and low-cost alternatives such as wetlands and other passive systems [58,59]. As discussed earlier, algae cultivation can be combined with the wastewater treatment process to reduce the energy footprint of these systems and may further produce biogas if possible.

5. Water for energy production

Eighty percent of the electricity in U.S. is generated by thermoelectric facilities that require cooling water and only about 8% by conventional hydropower. About 43% of the existing power plants in the U.S. employ once-through cooling and this demand is expected to increase in the coming decades indicates the need for new, reliable and inexhaustible freshwater sources [60]. This need also provides impetus for developing water-efficient cooling systems for power generation. The water intensity of a fuel source is defined as the amount of water required per unit of fuel produced. The water intensity varies significantly from source to source. For example, conventional natural gas has very low (negligible) water intensity (less than 1 gallons of water per

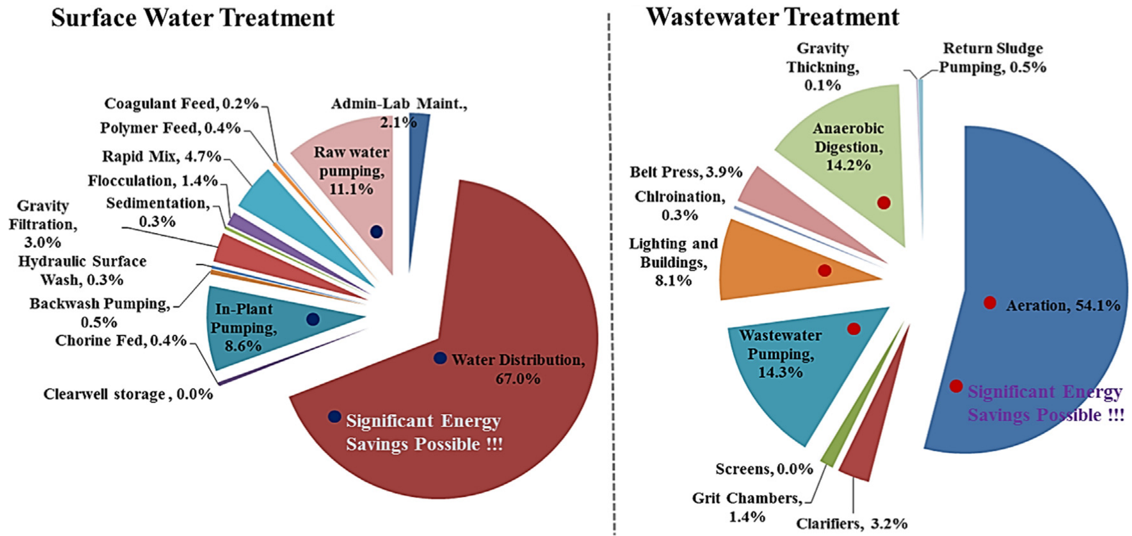

Fig. 7. Distribution of energy requirements for conventional water (a) and wastewater (b) treatment operations and processes.

Table 2
Water withdrawals and consumption in cooling towers [63].

	Cooling technologies—water withdrawal (L/MW h)					Cooling technologies—water consumption (L/MW h)				
	OL	CL	CL-CT	HC	AC	OL	CL	CL-CT	HC	AC
Coal	132,000 (±57,000)	1,700 (±500)	2,100 (±200)	Between	<400	1,100	1,500 (±400)	1,800	Between	200 (±40)
Nuclear	161,000 (±66,000)	3,000 (±1,100)	3600 (±600)	Between	<400	1,500	2,400 (±850)	2,700	Between	200 (±40)
Natural Gas Combustion Turbine	Very low	Very low	Very low	Very low	Very low	Very low	Very low	Very low	Very low	Very low
Natural Gas Combined-Cycle	52,000 (±24,000)	600 (±100)	900	Between	<400	400	500 (±80)	700	Between	200 (±40)
Integrated Gasification Combined-Cycle	Not used	Not used	1500 (±400)	Between	<400	Not used	Not used	1,300 (±400)	Between	200 (±40)
Concentrated Solar Power	Not used	Not used	3200 (±300)	Between	<400	Not used	Not used	3,200 (±300)	Between	300 (±40)

OL—open loop; CL—closed loop; CL-CT—closed loop cooling tower; HC—hybrid cooling; AC—air-cooling.

MMBtu); followed by coal, unconventional gas, and uranium mining (roughly 1 to 10 gallons per MMBtu, Table 2). Oil extraction has about 10 to 100 gallons per MMBtu of water intensity and biofuels from irrigated crops (100 to 1000 gallons per MMBtu) are on the higher end of the scale [61].

5.1. *Water consumption in thermoelectric power plants*

Water consumption occurs in almost every application and process utilization step. For example, the distribution of U.S.'s total water withdrawals are irrigation-livestock (85%); thermoelectric (3%); industrial mining (4%); and domestic-commercial (8%) respectively. The same for the water returns is very intriguing and is as follows: irrigation-livestock (23%); thermoelectric (53%); industrial mining (10%); and domestic-commercial (14%) respectively [62]. The difference between the distribution levels represents the consumptive nature of the process or application. Most of the water consumption losses are not the real consumption in a specific application but by the evaporation and evapo-transpiration (that by plants and soils) processes. Considering water consumption for electricity production, it appears that thermoelectric power plants consume large quantities of energy compared to others due to cooling water needs. If evaporative water losses from the reservoirs can be counted for hydroelectric power plants for electricity production, the specific water consumption would be 68 L/kW h of electricity, which is much higher than 1.8 L/kW h of electricity for thermoelectric power plants (Fig. 8). Since, the evaporative losses for the hydroelectric power plants are inevitable, let us now look at the specific process steps that involve water consumption at thermoelectric power plants. Water consumption by the power plants varies significantly depending on the type of cooling water technology implemented. For example, there are three main cooling options namely, open-loop cooling (1100 L/MW h or 1.1 L/kW h), cooling tower (1800 L/MW h or 1.8 L/kW h), and cooling reservoir (1500 L/MW h or 1.5 L/kW h) [63]. Thermoelectric power plants withdraw a tremendous amount of water with a small percentage being evaporated which is still of great significance based on today's water needs and environmental pollution issues. The plant typically consists of a boiler, steam turbine, coal clinker, steam condenser and cooling tower. The following types of water consumption occur in thermal power plants: (1) boiler feed-water; (2) circulating cooling water; (3) water for ash and residue removal; (4) cooling water for auxiliary equipment; (5) water for desulfurization and other small uses for coal yard cleaning (if applicable) and water consumption by general purposes such as drinking water supplies, general cleaning, and space and equipment cooling [64,65].

5.1.1. *Boiler feed-water*

A high pressure pump delivers freshwater into the boiler which converts into high-pressure steam. The steam enters the steam turbine to produce electricity and in turn loses the pressure and

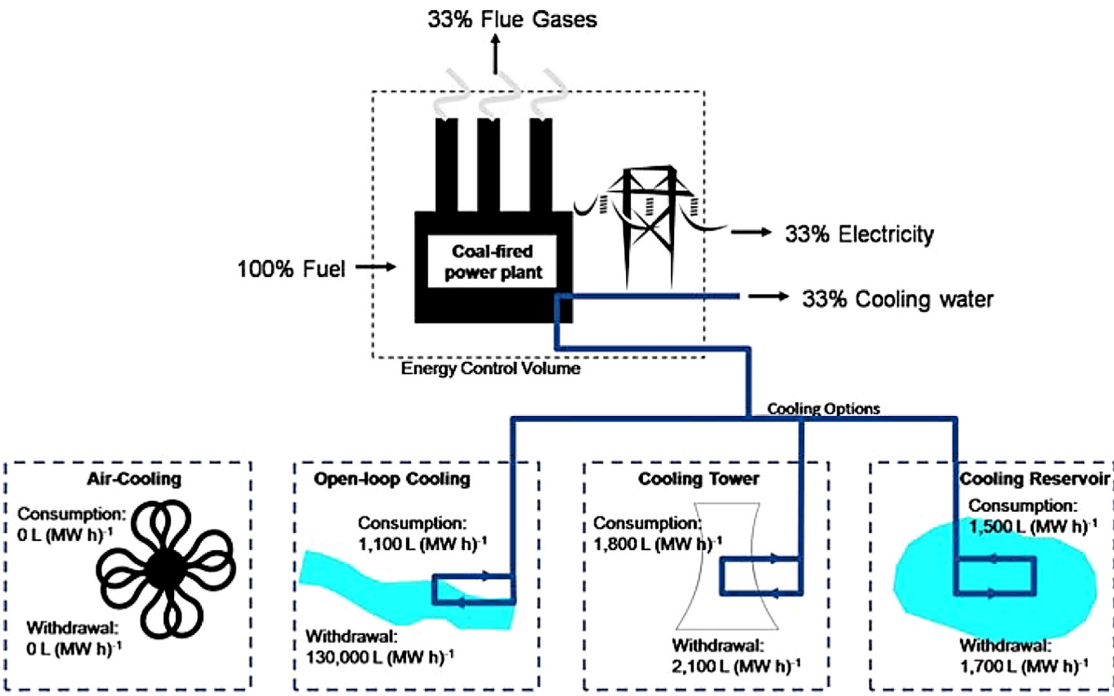

Fig. 8. Water consumption in power plants for different types of cooling options.

temperature due to exterior force and converts into water. This water is again pumped through the boiler in a circulating loop. In this process, some of the water is through boiler losses, ash-blowing loss, and steam leakage.

5.1.2. Cooling water

After the electricity production in the steam turbine, the steam needs to be condensed using cooling water from cooling tower. This step removes the large quantities of latent heat from the steam. While condensing the steam, some of the cooling water is evaporated by absorbing the latent heat. About 50 t of cooling water is required to condense every ton of steam. This process results in increase in cooling water temperature (by about 15 °C) which needs to be cooled down by circulating in the cooling towers. This process again results in loss of cooling water in the form of water vapors. Water loss due to wind blows is also another major factor for cooling tower water losses.

5.1.3. Water consumption for ash and residue removal

The water removal of ash and residue is to rush the ash collected in the smog and the residue from the boiler to the ash yard and they are usually big reservoirs in many thermal power plants. The present large coal-fired units all equip with the dusting equipment, and the fly ash collected by the dusting equipment are used in building materials for construction.

5.1.4. Cooling water for auxiliary equipment

This cooling water includes all the cooling water except for the condenser of steam turbines such as cooling water in the generators, the cooling water for blowers and water pumps and these cooling water consumptions are not large. Indirect air-cooling with circulating cooling water in a closed loop can be used for these purposes.

5.1.5. Water for desulfurization

Desulfurization equipment is required to remove the sulfur dioxides from the power plant stack gases. This is done in absorption towers and scrubbers, which require significant amounts of water. In

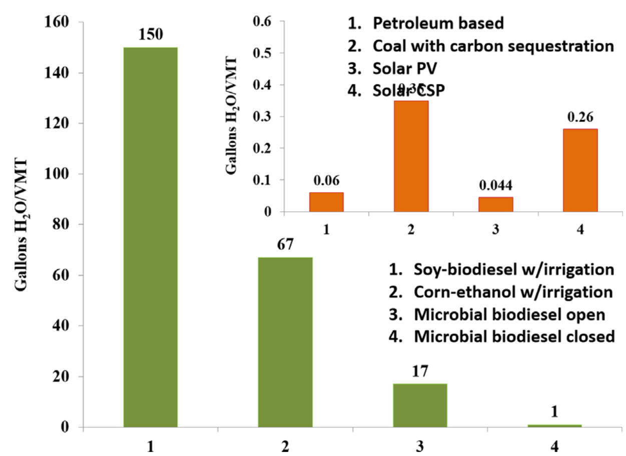

Fig. 9. Water requirements for clean energy production from different energy sources.

the scrubbing process sodium or calcium based alkaline reagent is injected in the spray tower to absorb the SO_2, neutralize into a solid compound, either sodium or calcium sulfate. Scrubbers can be "once-through' or "re-generable". Again, there are three types of scrubbers, wet, semi-dry or spray dry, and dry systems. In US, 85% of the systems are wet, 12% are spray dry and 3% are dry scrubbers [66]. The desulfurization removes over 99% sulfur. Dry desulfurization systems could be adopted to save water. Other water uses for coal yard cleaning (if applicable) and by the power plant personnel could add a small portion of water demand.

5.2. Water consumption for renewable energy sources

Renewable energy sources can play a critical role in the global energy supply-demand system. A renewable energy source can only be considered sustainable if it is available in sufficient quantities or can satisfy a considerable fraction of present and future energy demands; it should be generated from readily available renewable sources, land and water demands must not be prohibitive and price

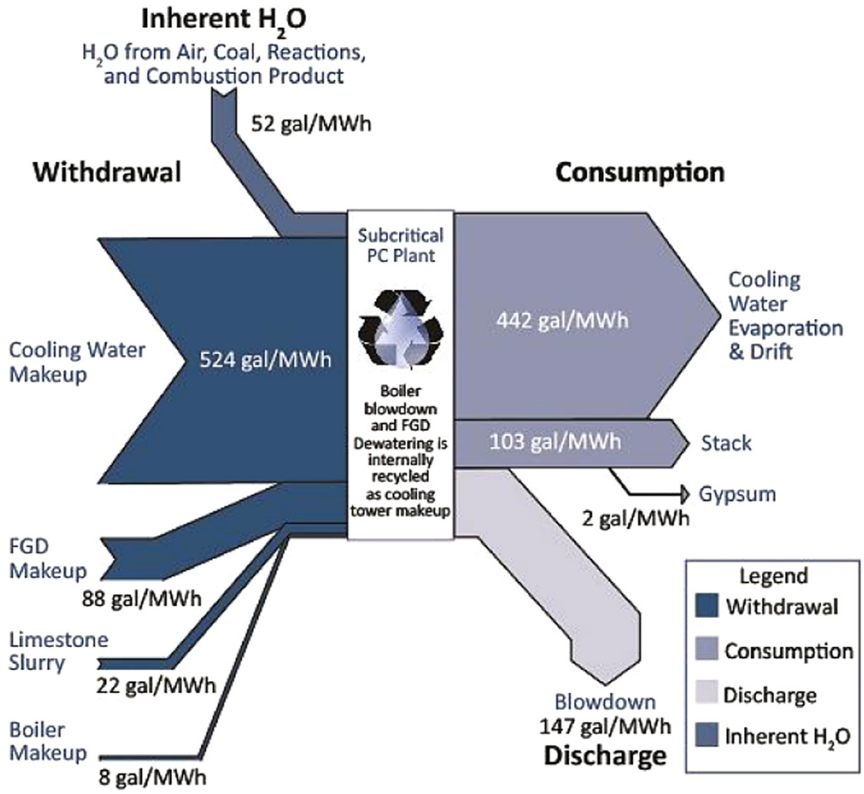

Fig. 10. Water balance on a subcritical, pulverized coal, 500-MW power plant with a cooling tower and wet FGD.

must reach grid parity in the near future. At present, photovoltaics appear to be highly promising and possibly supplemented by solar thermal electricity production [67]. Gasoline production from fossil fuels (considered nonrenewable) involves water consumption (about 3 gallons of water/ gallon of gasoline). Water is also required for irrigation of renewable fuel feedstock such as corn, soybean and switch grass and solar based technologies. The amount of water required for irrigation varies significantly from one region to another. Gallons of water required per vehicle mile travelled (VMT) for different energy sources are shown in Fig. 9 [68]. Biofuels from corn and soybean crops requires significant amounts of water throughout the entire life cycle, but biodiesel production from microalgae appears to have much smaller footprint indicating a future growth potential in this area.

6. Opportunities for water conservation and savings in power plants

Of the 1655 operable cooling systems in the United States, 875 (53%) reuse water either through a cooling tower or a cooling pond, while 719 (43%) do not reuse water. The remaining systems are either dry (56 systems) or hybrid (5 systems), which can switch between dry and some sort of wet cooling depending on the temperature and availability of water [69]. Fig. 10 shows the water balance of a pulverized coal thermoelectric power plant with a wet cooling tower [70]. Water withdrawal for cooling water makeup quantity counts up to 76% followed by the water requirements for flue gas desulfurization (13%). It can be noticed that about 85% of the makeup cooling water is lost through evaporation and drift losses in the wet cooling tower. This indicates a potential stream for significant water savings in the power plant. Thermoelectric power plants in the past were supported by once-through cooling water systems. These systems consumed about 20–50 gal of water (70–200 L) to generate each kW h of electricity. The Clean Water Act—Section 316(b) discouraged the design and construction of once-through cooling systems. Power plants built after 1980, withdraw much less water for cooling purposes for modern cooling systems but consume most of what they withdraw by evaporative cooling [60]. The need for water self-sufficiency can be motivated by other factors such as drought and population growth, increased emphasis on environmental flows (nature restoration), water independency, and constrained infrastructure-limiting capacity for water supply and drainage [60,71]. Hydroelectric and thermoelectric generation plants can be suspended under drought or low flow conditions in the water bodies or these conditions may become barriers for approving new plants. These limitations on freshwater sources are more common in west and southwest regions of the U.S. Therefore, it is necessary to consider more water efficient and more promising technologies to reduce cooling water requirements in power plants. The two main principal pathways would be to find new and sustainable water sources that can potentially serve as cooling water such as treated effluents and seawater sources or by improving the water-efficiency of the existing cooling water technologies through dry cooling or hybrid cooling [72]. The following sections discuss the available options to improve the water-autarky of power generation systems.

6.1. *Dry cooling*

Evaporative cooling towers in thermal power plants can be replaced by dry cooling technology. Dry-cooling technology is an attractive alternative to wet-cooling technology that allows power plants to reject the heat to air, directly or indirectly, without any loss of water [73]. The eminent advantages of dry-cooled power plants include: minimal freshwater consumption [74]; flexibility in plant siting that enables power plants to be located closer to load centers rather than to cooling water resources [75]; minimized risk for Legionella health risks [76]; and reduced rates of plume formation and brine disposal [77]. The major disadvantage of dry-cooling technology is that they use ACCs (air-cooled condensers) whose performance declines with increasing ambient air temperatures, and thereby induces cycle penalties in the associated power plants. The effectiveness of ACCs has been reported to reduce by at least 10% due to high ambient temperatures in summer [73,78]. Table 2 shows the water withdrawals and consumption ranges for various cooling water options [63]. Dry cooling or air cooling towers have minimum water consumption, least compared to other cooling technologies. But this technology suffers from low heat transfer capabilities (air has significantly low specific heat capacity) compared to wet cooling systems, requiring large heat transfer areas for effective heat transfer in both hot and cold seasons as well as dry and humid weather conditions. Cooling system power requirements for dry systems are four to six times those for wet systems. Dry systems, which are limited by the ambient dry bulb temperature, cannot achieve as low a turbine back pressure as wet systems, which are limited by the ambient wet bulb. Therefore, heat rate penalties and capacity limitations are incurred at some sites depending on local meteorology [12].

6.2. Hybrid cooling

Dry and wet cooling systems can be combined to reduce the cooling water footprint with a better hot-season performance. These systems help reduce plumes, and vapor exhausts that could potentially cause foggy conditions around the power plants. Hybrid cooling systems such as spray cooling over air-cooling condensers have issues such as scaling and corrosion of the condenser surfaces. They are recommended for enhanced cooling application not exceeding a few hundreds of hours per year [77]. An alternative approach useful during extended operation is a parallel wet/dry system, which uses a dry tower and a conventional evaporative cooling tower to augment cooling in the hottest weather for small-scale applications [79]. Finally, hybrid cooling despite marginally higher costs and emissions, would reduce dependence on scarce water resources thus increase security of energy and water supplies [72].

6.3. Use of wastewater as cooling water

Domestic wastewater effluents may serve as ideal cooling water source due to availability and acceptable water quality (Fig. 11). Blending treated wastewater effluents with the makeup water streams is already being practiced at many power plants. For instance, Redhawk Power Plant in Arizona uses treated effluents for over 90% of the cooling system makeup approximately 6.46 million gal/d (MGD; 24.5 ML/d) [60] and in some power plants up to 100% of the cooling water needs are met by the treated wastewaters [80] In another application, the wastewater effluent was injected through a geothermal field to convert it into steam suitable for electricity production. This system is in operation since 1990 with a power generation capacity of 100 MW. Yet, another creative approach was to utilize the effluent drop in the injection wells to convert kinetic energy into additional electricity (250 kW/yr) Northern California Power Agency [81]. The chemistry of treated effluents does not have significant effect on the cooling performance, moreover, the economics of wastewater effluent reuse for cooling seem to be attractive compared to the freshwater sources [82,83].

6.4. Seawater for cooling and then water production (co-location with desalination plants)

In some cases, more than a single use for cooling water could provide additional benefits. Seawater can serve as an excellent source for cooling water medium with some pretreatment. Since the cooling water (sweater) from the power plant is already passed through a pretreatment process similar to desalination plant seawater intake, use of this discharge water as feed for desalination plant (e.g., reverse osmosis) is well justified. Therefore, co-locating desalination and power plants would seem beneficial eliminating the need for redundant pretreatment systems (intake structure, pipelines and screening facilities) [84]. Since cooling water discharge has a higher temperature, the membrane flux (productivity) increases while at the same time reducing the energy consumption. However, higher feedwater temperature may provide ideal conditions for biological growth on the membrane modules causing biological fouling.

Co-location of a power plant with a seawater desalination plant was demonstrated at Tampa Bay and this scheme is being considered for numerous plants in the United States and worldwide. At the Tampa Bay Seawater Desalination Plant, the intake and discharge are connected directly to the cooling water discharge outfalls of the Tampa Electric Big Bend Power Station [85]. The cooling water discharged from the power plant is 3 to 8 °C (5 to 15 °F) warmer than the ambient source ocean water. This is a significant benefit because the RO process requires approximately 5 to 8% lower feed pressure when the influent seawater is an average of 6 °C (10 °F) warmer. However, Tampa Bay Water reports that there are times when the power plant cooling water is too hot to use for desalting membrane operations, which has required the water utility to develop and periodically operate their own intake. Co-location offers several benefits including significant permit cost savings, energy cost savings in desalination plant, eliminates the need for intake structure costs, eliminates grid transmission power fees [85]. Co-location also provides numerous environmental benefits related to coastal ecological systems [86].

Energy storage might help reduce some of the water consumption due to matching between the peak and off-peak demands and power production schemes. Water can be used as the medium for thermal energy storage. Additionally, use of other forms of phase change materials for cooling and storage purposes might

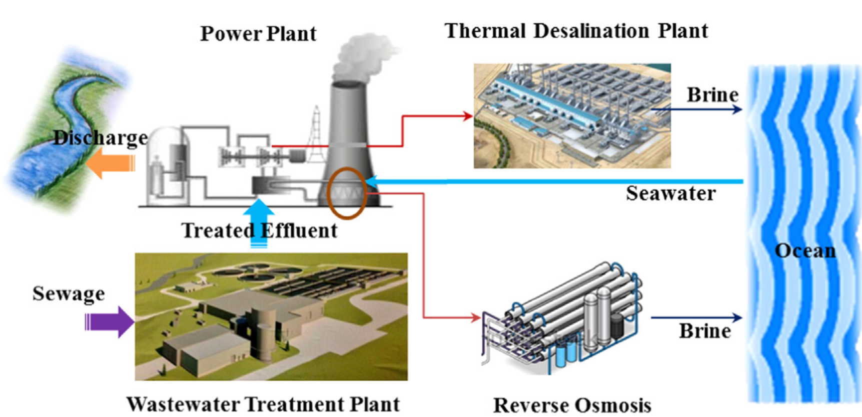

Fig. 11. Co-location of desalination systems and wastewater treatment plants with power plants.

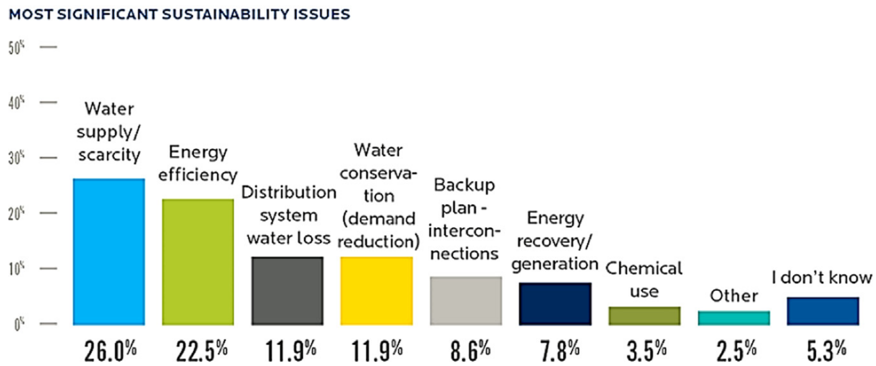

Fig. 12. Survey results from the water utilities on significant sustainability issues.

help increase energy densities and storage capacities but these systems can be cost-intensive [4]. Generally, purified water is the most economical storage medium in these applications. This type of energy storage option might be feasible in specific applications and regions where adverse effect of water resources are highly pronounced such as in arid regions. In power generation and desalination co-generation schemes, energy storage can play even better role since the desalination systems depend on electrical energy supplied by the power plants.

6.5. Energy from renewable energy sources

Clean energy and water production involves utilization of environmental and land resources and their degradation due to release of air pollutants (greenhouse gases and other toxic pollutants) and waste products. However, when renewable energy sources such as solar, wind, geothermal and biomass based sources are considered, the environmental impact is well reduced. Moreover, the environmental emissions and energy payback periods, for these energy resources, are very reasonable. For example, solar collector system for domestic hot water needs has environmental emissions and energy payback periods of less than 2 years (i.e. the energy requirements and environmental emissions that incurred in their production from raw materials) with life span of 20–25 years [87]. Thus, renewable energy source utilization for clean water production can offer sustainable solution where applicable with minimal environmental impact. Similarly, developing water-efficient (with water recycling and reuse) renewable energy sources will reduce the water footprint for energy production.

Considering biomass sources for energy production, major water consumption comes from crop irrigation or cultivation. About 10–17 l of water are consumed to produce one liter of ethanol and water requirements for switchgrass ethanol production vary from 1.9 to 9.8 l for each liter of ethanol produced [88]. As a comparison, 2.8–6.6 l of water consumed for each liter of gasoline produced from conventional onshore sources in the U.S. and more than half of crude oil imported from Saudi Arabia. As shown in Fig. 9, fuel-producing crops such as corn and soybean seem to be quite water demanding when compared to microalgae source. When a closed system is considered, the water footprint is significantly reduced albeit at a higher capital investment. These comparisons indicate that even more careful water source planning and management is required for renewable energy production.

7. What can be done for the future projects?

Although not always apparent, energy and water are increasingly interdependent resources. While achieving autarky in individual systems is an attractive endeavor, the current and the foreseeable trends indicate that water and energy problems of the future will continue to become more complex, and intertwined with each other and other development sectors like agriculture, industry, transportation, and with social sectors like education, environment, health, and rural or regional development. These two essential commodities can no longer be dealt with in isolation but an integrated approach with consideration of other related sectors and issues is required [89]. Water supply and energy production issues can vary largely influenced by the region. Fig. 12 shows the results of a survey conducted among the water treatment utilities to determine the most significant sustainability issues for the present and the future. About 50% of the responses indicate the water supply/scarcity (26%) and energy efficiency (22.5%) as most significant issues and needing immediate attention [90]. This survey was conducted by Black and Veatch among the water utility participants and about 90% of the participants indicated that their organizations are currently implementing or are interested in implementing energy efficiency programs which include energy efficiency optimization and management, renewable energy integration such as solar power, hydropower, and wind power, cogeneration/CHP and energy recovery from biosolids. Therefore, in addition to developing novel and efficient technologies, synergistic and holistic approaches should be considered to develop sustainable power and water systems.

A few options to consider will be to improve infrastructure for synergistic energy and water production, collaborate resource planning, and develop science and system based policies and regulations and infrastructure synergies. Synergistic energy and water production involves cogeneration (co-production) of energy and water by co-locating the power plants adjacent to wastewater treatment facilities and brackish water sources to reduce the need for freshwater needs. Similarly, waste heat from power plants can be used in some desalination cycles, and biogas from wastewater treatment plants can be used to generate electricity. In systems context, energy-water integrated infrastructure would result in significant water and energy conservation. Collaboration on energy and water resource planning among federal, regional, and state agencies along with industry and other stakeholders would help secure sustainable development of these sectors without impacting their production in the future. For example, new power plants have been declined in the three fastest growing regions in the country, the Southeast, Southwest, and the Northwest due to potential negative impacts on water supplies. Recent droughts and emerging limitations of water resources have restricted states like Texas, South Dakota, Wisconsin, and Tennessee, from new developments. Mechanisms, such as regional natural resources planning groups, are needed to foster collaboration between stakeholders and regional and state water and energy planning, management, and regulatory groups and agencies to ensure proper evaluation and valuation of water resources for all needs, including energy development and generation. Finally, polices or regulations developed to support or enhance one area, such as increasing domestic energy supplies could have unintended negative impacts on regional or national freshwater availability or water quality. System-level evaluations by stakeholders and government agencies can be used to assess the impact of current or proposed natural resource policies and regulations and improve future energy development and water availability. All these strategies will certainly enhance the self-sufficiency of individual or integrated systems and help achieve sustainable water-energy infrastructure development.

Acknowledgements

This research was supported by the Office of Research and Economic Development (ORED), Bagley College of Engineering (BCoE), and the Department of Civil and Environmental Engineering (CEE) at Mississippi State University. The author would like to acknowledge the funding support from the United States Environmental Protection Agency (USEPA) under P3 (People, Planet, and Prosperity) Awards program through the grants SU835721 and SU835722.

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