Water Energy Nexus for Water Distribution Systems: A Literature Review

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Water Energy Nexus for Water Distribution Systems:  
A Literature Review

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ABSTRACT

Water and energy are interdependent on each other. Energy is required to supply water to a system while, at the same time, water is needed for power generation in any natural or artificial system. This relationship is often called the Water-Energy-Nexus (WEN). In a water supply system, energy is consumed for source water extraction, transmission, treatment, and distribution. About 7-8% of the world’s total generated energy is used for drinking water production and distribution. A major portion of this energy is used for distribution, i.e., pumping, chlorination, and maintenance activities, and hence is the focus of this review. Most of the world’s energy is generated by fossil fuels (oil, gas, and coal), which results in greenhouse gas (GHG) emissions. Here we review studies conducted to assess and evaluate the energy consumption and the related GHG emissions in water distribution systems (WDSs). This review covers the basic concepts and studies on WEN, energy saving solutions, renewable energy resources for water pumping, optimization of design, and the life cycle assessment (LCA) of large WDSs. Most of the reviewed studies suggest a trade-off between energy cost and the associated GHG emissions when selecting fixed speed pumps over variable speed pumps for large WDSs. To mitigate CO₂ emissions, renewable energy resources like solar, wind and mini-water turbines for water pumping have been discussed and mini-water turbines were found to be energy efficient solutions. The energy focused LCA model has been studied to investigate the environmental impacts, GHG emissions, operational energy, and various life cycle stages of pipe manufacturing (embodied energy) in the network. Case studies of real world WDSs are reviewed and the potential research gaps are identified. Most life cycle studies have focused on the areas of pipe replacement, the life cycle cost of the system, the operational energy, and the reduction of GHG emissions, while less attention has been paid to the geographical and socio-economic issues, along with the areas of human health, water resource diversity, and the hydraulic characteristics of WDSs.
1 Introduction

In any modern society, a safe, continuous and adequate drinking water supply should be made available to every individual. Public water utilities and private suppliers obtain water from surface water (lakes, rivers, and sea water desalination) or groundwater sources to meet the demand of consumers in their service areas. The International Energy Agency statistics show that about 590 billion m³ of drinking water is being distributed by the water utilities around the world (IEA 2012). This contributes to nearly 10-15% of the world’s overall water withdrawals (Venkatesh et al. 2014).

It is estimated that about 7-8% of the world's total generated electricity is used for drinking water production and distribution systems (Yang et al. 2010; Coelho et al. 2014). Although water resources managers are putting serious effort into water conservation through performance benchmarking of their WSS (Haider et al. 2014), water demand is continually increasing every year with the growing population (Wakeel et al. 2016). A large portion (~ 65 %) of the total electricity in the world is generated by fossil fuel (coal, gas, and oil) power plants, while the remainder comes from other sources like hydel, nuclear, and renewable, which contribute about 10 billion tons of CO₂ emissions (IEA 2016; CAMRA 2012). In the USA alone there is about 520 million MWh per year of water-related energy use, which produces 295 million tons of CO₂ emissions per year (Griffiths et al. 2009). Energy generation through fossil fuels contributes to climate change and environmental pollution (Schaum et al. 2015; Stokes et al. 2014; Tabakovic et al. 2012). A substantial part of this energy is being used by water supply systems (WSSs).

Water and energy are fundamental natural resources. Fresh water is used for energy production, refinement, processing, transportation, storage, and the generation of electric power. On the other hand, energy is required by all the components of a WSS, including groundwater extraction, surface water withdrawals, transmission, treatment, and distribution (World Energy Council 2010). This interdependent correlation is commonly known as the “Water-Energy-Nexus” (WEN) (Gleick 1994; Nair et al. 2014; Schaum et al. 2015; Tabakovic and Poci 2012). Over the years, this idea has gained much attention due to increasing demand and rising energy prices. A typical water-energy-nexus (WEN) cycle is shown in Figure 1.
Water distribution systems (WDSs) are the largest energy consumers among the components of a WSS (CEC 2005; Gleick 1994). The energy consumption per unit volume in a WDS depends upon the size of the network, the topography, population, and the demand variations (Nair et al. 2014; Wakeel et al. 2016). There are two main types of WDS: i) centralized, which is a conventional system of water distribution through gravity, pumping, or pumping with storage; and ii) decentralized, which are generally smaller in size and integrates water conservation strategies with the conventional system, such as rain-water harvesting, recycling and the reuse of wastewater (Nair et al. 2014). This review article covers research published on all aspects of WEN for a conventional centralized WDS, including basic concepts, energy indicators, energy optimization, and life cycle analysis. Energy consumed in decentralized systems and other components of a WSS (i.e., extraction, transmission, and treatment) is beyond the scope of the present review. The findings will identify the existing research gaps and the need for more in-depth investigation into existing energy consumption patterns in WDSs to plan future strategies for optimizing energy consumption and reducing carbon emissions.

The approach adopted for this review is to identify the existing knowledge gaps in the different research areas of WEN, primarily of large-sized WDSs, is illustrated in Figure 2. This includes energy consumption, GHG emissions, optimization, pumping operation, booster pumps, and the life cycle stages of pipe manufacturing (embodied energy) in the network. More than 170 research articles and reports were consulted. The research was geographically distributed primarily between North America, Europe, Australia, and Asia.

The organization of the paper is as follows: Section 2 explains the background of energy consumption in WDS, WEN, and energy saving solutions. Various methodologies for the optimization of a WDS and the use of renewable energy resources, such as an alternative power source, are discussed in Section 3. Section 4 demonstrates various case studies on life cycle analysis (LCA) and the sustainability of a WDS. Section 5 presents the conclusion and future recommendations.

Insert Figure 1 here

Insert Figure 2 here
2 Background

2.1 Energy Consumption in Water Distribution Systems

Presently, water utilities aim to operate their WDSs for: i) providing safe water to their consumers by eliminating contaminants and minimizing the chlorine by-products, ii) maintaining low operational costs by maximizing energy efficiency and asset management practices, and iii) minimizing GHG emissions throughout the lifecycle (Sharif et al. 2017; Haider et al. 2014; Bolognesi et al. 2014; Haider et al. 2015). Energy saving in a large WDS depends in large part on process improvement, efficiency targets, and pumping efficiency (Cabrera et al. 2010). Due to high energy prices and the associated GHG emissions, there is an increasing demand to minimize energy requirements and to develop and implement sustainable water use strategies (U.S. Department of Energy 2006).

The energy utilization in a WDS depends primarily on energy source, water quality, type of pumping system (continuous ~ intermittent), size of distribution network, the age and network material, type of land use (required pressure head), and the topography of the area (Kenway 2008; Plappally et al. 2012; Lee et al. 2017). Table 1 summarizes some of the past studies that have presented data about the energy consumed by various WDSs around the globe. The average GHG emissions are presented in Table 1 (USEPA 2014).

For instance, in the state of Virginia (USA) a small town called Louden, which is located in a mountain valley with a population of about 40,000, used 2.28 kWh/m$^3$ of energy for distributing water to its consumers. In contrast, in flat terrain in the town of Alexandria, located in Virginia, with a population of around 155,000 (2016) used 0.55 kWh/m$^3$ of energy, which is 3 times less than in Louden (Alanis 2009). The variation in energy usage in both places is due to the topography of the network.

An efficient water distribution system, which receives good water quality, in the city of Auckland (New Zealand) consumes 0.21 kWh/m$^3$ energy. While the WDSs in Taipei, Taiwan consume energy varying from 0.26 to 0.51 kWh/m$^3$ because of the large number of chlorine booster stations needed to avoid the possibility of bacterial contamination due to the aging pipe infrastructure and the relatively poor source water quality (Lee et al. 2017).

Figure 3 shows the breakdown of total energy consumed (i.e., 0.40 kWh/m$^3$) by different components in a typical North American drinking WSS with a surface-water source on flat
terrain (EPA 2013). It can be seen that more than 75% (i.e., 0.3 kWh/m$^3$) of the total energy is consumed for water distribution.

**Insert Figure 3 here**

WDSs in Canada and some European countries are more energy intensive. For example, in Toronto (Canada), Nantes (France), Oslo (Norway), and Turin (Italy), water utilities have energy demands varying between 0.16 and 0.41 kWh/m$^3$ and emission intensities ranging from 0.006 to 0.16 kg/CO$_2$-e (Venkatesh et al. 2014). In Germany, an urban WDS consumes 1.71 kWh/m$^3$ of energy, which is 6 times higher than in China (i.e., 0.6 kWh/m$^3$) (Plappally et al. 2012; Smith et al. 2016). The primary reasons are: i) the type of supply, i.e., direct pumping for continuous supply in Europe contrasted with pumping with storage or intermittent supplies in developing countries; and ii) the required pressures along the network.

Countries in the Arabian Peninsula, including Saudi Arabia, Kuwait, Egypt, and Libya, have used fossil fuels to operate their WDS, and thus they produce a large amount of carbon emissions (Siddiqi et al. 2011; Al-mutrafi et al. 2018).

Water utilities relying on natural resources, such as hydel and wind-driven energy, produce far less GHG emissions. For instance, in the Portuguese city of Aveiro, a medium-sized WDS consumes electricity generated by hydel and wind power; as a result, negligible CO$_2$ emissions were reported (Afonso et al. 2011).

Various important factors, including climate change, growth in population, health, and environmental impact, can influence the development of an integrated approach to the WEN (U.S. Department of Energy 2006). The sources of energy and their consumption patterns using different components of a WSS, along with the associated environmental impacts during the complete life cycle, should be carefully analyzed to achieve a sustainable WEN (CEC 2005; World Business Council for Sustainable Development 2009; Water in the West 2013).

**Insert Table 1 here**

### 2.2 Energy Indicators

Over the last two decades, several “energy indicators” have been developed to: i) identify the factors responsible for the wastage of energy in a WDS; and ii) prioritize decisions that improve system performance (Prosser et al. 2013; Cabrera et al. 2010). A summary of water-energy efficiency indicators and their applications is presented in Table 2.

**Insert Table 2 here**
Pelli and Hitz (2000) introduced two primary energy efficiency indicators known as a quality indicator and an infrastructure indicator. A quality indicator is the ratio of the minimum theoretical energy to the actual quantity of delivered water in the network and is used to calculate the individual pressure zones in a simple WDS (Indicator E1 and E2 in the Table 2). However, the quality indicator can neither effectively estimate the minimum energy for each pressure zone in a complex network nor consider the structural characteristics e.g., the energy dissipated due to friction, water loss, and the total length of the network. Later, Colombo and Karney (2002) proposed additional energy indicators such as pump efficiency and energy dissipation due to friction. Filion et al. (2004, 2009) have analysed the environmental impact indicators associated with pipe fabrication and its disposal energy, in addition to the end-of-life stages of a WDS (Indicator E3 and E4 in the Table 2).

Boulos et al. (2010) developed ‘water network energy efficiency’ indicators to reduce the additional hydraulic energy dissipated in the network. These indicators apprise the system rezoning, upsizing of the water-mains, use of surplus hydraulic energy, and suggested pumping tradeoffs. However, the study did not consider the energy lost due to leakage in the entire network and the life cycle energy assessment of distribution systems.

Cabrera et al. (2010) proposed an ‘energy balance indicator’, also known as an ‘excess of supplied energy’. They also developed five additional indicators to assess the energy efficiency of a WDS, including an excess of supplied energy, network energy efficiency, leakage energy, standard compliance, and energy dissipated through pipe friction (Indicator E6 in the Table 2). EPANET simulations were performed to develop these indicators assuming a flat surface, frictionless pipes with no leakage, and service to low pressure heads. The study did not consider the energy cost and embodied energy over the life cycle of a WDS.

Bolognesi et al. (2014) proposed an energy efficiency indicator ‘the ratio of unavoidable minimum energy to actual energy’ for WDS. This indicator can be used as a reference starting point to assess the actual use of energy, the impact of leakage, and pipe replacement in the network (Indicator E8 in the Table 2). Bolognesi et al. (2014) used the model of Cabrera et al. (2010) to study the pumping energy variable of distribution networks. They included the energy efficiency of pumping systems and a pressure dependent demand to express the leakage rate, which was not taken into consideration in previous studies. Scanlan (2016) extended the study proposed by Cabrera et al. (2010), applying energy indicators to assist the operators regarding
energy use. This study characterized four real small to medium-sized WDSs in Ontario, Canada, and assessed the energy lost due to friction, leakage, and excess energy (Indicator E10 in the Table 2). It was found that energy efficiency can be improved from 75% to 94% without leakage in the system and from 58% to 70% with leakage. Hypothetical system characteristics like topography, hydraulics redundancy, and peak demand were assumed. The term ‘minimum energy value’ was used by water utilities as a reference baseline to assess the actual energy consumed. This is an unavoidable energy value that is required by any system to maintain the minimum pressure to run the network. The assessment of the minimum energy baseline is complicated for a larger and more complex network because it varies with system configuration (Lenzi et al. 2013).

In the past, few researchers have developed “energy indicators” to assess the wastage of energy during the operations of WDSs. The decision makers are planning, prioritizing, and making affordable strategies to reduce energy incompetence. Applications for these indicators in real-world distribution systems are limited to date. However, a few studies have described the energy efficiency indicators of a real large system to assess the actual use of energy, pipe breakage, leakage reduction, pump repair or replacement, and the related GHG emissions (Dandy et al. 2008; Boulos et al. 2010).

3 Energy Saving Solutions

3.1 Watergy

“Watergy” is a recent term which was developed with the aim to provide energy saving solutions, through technical and managerial interventions, for conserving water without interrupting the desired uses (Barry et al. 2007). The successful implementation of this tool around the world has revealed immediate improvements in water delivery systems, energy saving, and water price reductions (AWWA 2003; Barry et al. 2007). The concept of WEN has not yet been broadly understood or adequately explored through synchronized, holistic efficiency approaches. The water energy saving approach consists of three main steps, including creating the political will, technical management, and implementing efficiency measures (Barry et al 2007).

In a WDS, cost-effective benefit analysis improves the energy efficiency and reduces the payback period. Energy efficiency can be improved in all segments of a distribution network
through regular checking of the pumping systems, energy recovery through in-conduit hydroelectricity, managing leaks, metering and monitoring, automation, and asset management (Barry et al. 2007). A EPA (2013) report states that a water utility in the U.S. can save about $400 million and 5 billion kWh annually through cost-effective energy conservation techniques. Interested readers are referred to Barry et al. (2007) for details.

3.2 Optimization and Maintenance of Pumping Systems

Recent studies have revealed that most of the operational cost in a WDS is associated with water pumping (Marchi et al. 2012). For example, more than 6-7% of the electricity in California is being used for water pumping systems (CEC 2005). According to the U.S. Department of Energy (2006), about 10 to 30% energy savings can be achieved by optimizing the pump sizes, while the appropriate use of variable speed drives can save an average of 10% of the total electricity required for water distribution. The main obstacles in operating WDSs at high efficiency are their complex networks with large spatial variations, unreliable structure, and time-varying parameters (Swamee 2008). Utilities strive to optimize the operational energy of their WDSs without compromising on hydraulic performance (i.e., desired flows and pressure heads) and system reliability (i.e., minimum interruptions). Preserving the operational security of the system, by maintaining the hydraulic performance when part of the system is non-operational, might lead to higher energy costs (Coelho et al. 2014).

It also reported that investing 8 cents/kWh on maintenance of pumping systems can: i) increase pump performance by about 20%; ii) provide savings of 145,100 kWh/year of energy and $11,800 in energy costs; and iii) reduce emissions by around 98 tons CO\textsubscript{2} per annum. The three types of pumps (centrifugal, vertical, and submersible) that have been used in WDS depend on network size. The most commonly used type of pump for the delivery of large flows with a stable head is the centrifugal pump (HydraTek 2013). Instead of using a fixed-speed pump (FSP), both the energy use and the GHG emissions can be reduced with the help of a variable speed drive pump (VSP). The optimization of the FSP has been noted in many studies (Wu et al. 2012). The VSP is useful in networks where the water demand varies (close pressure zones) and the pump size is not a deciding factor (Wegley et al. 2000; Rao et al. 2007; da Costa et al. 2008; Wu et al. 2009). Marchi et al. (2012) evaluated the performance of both the FSP and VSP in a small system (population less than 20,000). They found that the FSP consumed more energy
(i.e., 0.4 kWh/m$^3$) in comparison to the VSP (i.e., 0.23 kWh/m$^3$), which results in a savings of around 40% in pumping costs.

A pump’s efficiency decreases due to wear and tear, and with age it starts consuming more energy. A few water utilities in Ontario, Canada have adopted the use of refurbished pumps in WDS which has resulted in significant reductions in energy, operational cost, and GHG emissions. HydraTek (2013) tested the efficiencies of 152 pumps operating in various water utilities spread all over the province of Ontario. The annual energy consumption and GHG emissions of all of the tested pumps were found to be 161,230 MWh and 27,400 tonnes of CO$_2$, respectively (Environment Canada 2011). It was found that, after refurbishing these pumps, 11% of the pumps recovered their lost energy efficiency. The results show improvements in both the pump energy indicator and volumetric efficiency after refurbishing 34-year-old pumps in a large WDS (HydraTek 2013).

Micro-pump storage activities, such as pumping at night and in-conduit hydropower generation, are energy savings options (Marchis et al. 2014). Various researchers have investigated the possibility of recovering water energy by the application of mini hydro-power plants.

Water conduits have enormous untapped potential to recapture energy for small-scale hydroelectric generation, which can significantly reduce grid electricity consumption and provide renewable energy to the water pumping system (Sari et al. 2018). In recent years, the in-conduit hydroelectric turbine system “water to wire” has received more attention due to its simple framework. These mini/micro hydro-turbines, including reaction, impulse, and hydrokinetic, can produce 10 kW to 1 MW of electricity (FERC 2017; Telci et al. 2018). The main advantages of mini/micro hydro-turbine systems include ease of installation, minimizing environmental impact, higher efficiency as compared to wind and solar, and less output power variations (Sari et al. 2018). North American and European countries are successfully operating WDSs using mini/micro hydropower plants. In the U.S. alone approximately 1650 mini hydropower plants with a combined generating capacity are producing about 3675 MW of electricity (Hadjerioua 2015). Unfortunately, thus far, high equipment costs and lack of exposure to water utilities have restricted these applications in WDS.

The use of a pump as a turbine (PAT) is an alternative power source for water distribution, which can save substantial amounts of energy (Marchis et al. 2014). Around the world, China has the highest installed capacity of mini-hydro turbines for power generation (Laghari et al. 2013;
Pressure reducing valves (PRVs) are commonly used to control hydraulic energy available in the drinking water pipe network. A small hydro turbine can be exercised to control the stream of water for electricity generation with no environmental impact (Ramos et al. 2011). However, mini hydropower generation is a less efficient method when compared to other renewable energy resources (Campbell 2010).

### 3.3 Leakage Management

Leakage in water mains is one of the most significant operational problems in a WDS. Water leakage usually occurs in broken and old buried pipes, water mains, valves and taps. A pressure management can significantly reduce leakage in WDS. Pressure management is more cost-effective than conventional expensive repairs to numerous leaks in buried pipes. Water utilities in Ontario, Canada have saved $2.6 million dollars in energy costs per year by implementing pressure management solutions (Maas 2009). Pressure reduction due to leakage results in a significant loss of embodied energy (CEC 2005). In developing countries, around 30-50% of urban supplied water is lost due to leaking pipes and system inefficiencies (Barry et al. 2007). For example, in large Indian metropolitan cities, about 40% of the water is lost due to leakage, and this figure varies from 50%-60% in smaller cities. Similarly, in most of the big cities in South Africa about 40% of the water is lost in the distribution system (Barry et al. 2007). Figure 4 shows the % of water lost due to leakage within the WDS in various countries of the world.

*Insert Figure 4 here*

In the U.S. a water utility requires a 14-m (head) minimum service level pressure (in fire flow condition), and in U.K this level is about 10-m (head) (at kitchen tap), to deliver water to every single user. Ideally, a 20-m water pressure head demonstrates good pressure throughout the WDS without extensive leakage (Boulos et al. 2010). A minimum level of energy is required all of the time to maintain an optimal pressure level in the WDS. Therefore, a 20-m water pressure head (a form of potential energy) is necessary to maintain a balanced pressure at every single customer tap (Boulos et al. 2010).

The European Commission (2010) has reported that living standards and other social aspects can have a great impact on water consumption by the end user; thus, an energy sustainable water management system is required in homes. Most of the energy is lost at the customer tap due to leaking tap washers, extra flushing water in the toilet, and lengthy showering times. In the U.K.
and Australia, the average time for a person taking a bath or shower is about 8 minutes, consuming about 0.04kWh/m$^3$ of energy (Walker et al. 2007). In the U.K. people kept their taps turned on while brushing their teeth. In London alone, about 25% of the water lost is due to the taps remaining unattended while they remained opened for an extended period (Walker et al. 2007). The results show that an average medium-sized U.S. WDS loses about 7% of water-energy in its pipes due to friction, 8% from overpressure, and 85% at the customer taps (plumbing fixtures) (Boulos et al. 2010). An enormous amount of energy is lost at the customer tap. This energy could be conserved by educating the public and implementing a pressure management system (PMS) at the users’ end.

Numerous utilities around the world have successfully applied the PMS to control leakage in their distribution networks. The pressure in a WDS can be adjusted by the use of pressure control valves, pump as a turbine, and variable speed drives (Philip et al. 2017). Usually, pressure reduction valves and variable speed pumps are the most common devices used to adjust water pressure and flow in a network (Monsef et al. 2018). The control system allows the water utility to manage and adjust the pressure automatically within the network with a slight increase or decrease in water input (Xu et al. 2016). Particular attention is required in case of intermittent supplies where high residual heads are not required as the supplied water is stored in underground storage tanks and distributed through in-house plumbing system (Haider et al. 2019).

One of the best practical applications of the PMS has been adopted by the water utility in the city of Emfuleni, South Africa. The town has a population of one million and utilizes about 200,000 m$^3$/day of drinkable water. After the implementation of the system, approximately 8,000,000 m$^3$/year of water and 14,250,000 kWh/year of energy was conserved, leading to a reduction of about 12,000 metric tonnes of GHG annually within a 3-year payback period (Barry et al. 2007; Wegelin et al. 2009). Table 3 summarizes the past studies of water energy management systems employed on large-sized WDS and medium-sized water utilities serving two- to three-story residential and commercial buildings.

Insert Table 3 here
4 Optimization of Water Distribution System

4.1 Optimal Design

The development of large WDS, without being optimized, cannot fulfill the growing future water demands of local communities (Kiselychnyk et al. 2009). Given the complexities of a WDS, such as the varying sizes of the pipes and the corresponding head losses, including variations in pressure and demand loads across the network, optimization problems can be resolved by using traditional trial and error techniques (Coelho et al. 2014). The use of a nonlinear optimization algorithm is more popular and efficient. The optimal solution always means minimizing the cost function or maximizing the benefit (reliability) function of the network subject to equality or inequality constraints, i.e., hydraulic system requirements (Veldhuizen et al. 2007). Various optimization studies have shown that one objective function may be suitable for one system while being inadequate for another system (Berge et al. 2000). No perfect algorithm has been developed so far that is able to solve all of the optimization problems of urban WDS. In the last three decades, the nonlinear (classical and heuristic) optimization approach has been used frequently to optimize network design and operation (Coelho et al. 2012). Figure 5 illustrates different types of nonlinear optimization algorithms for urban WDS.

Other optimization methods for WDS such as ant colony, particle swarm, simulated annealing, and harmony search have also been reported in the literature (Coelho et al. 2012). However, the main limitations of using these methods are their high computation times and the extensive effort required. Some researchers have used a multi-objective approach to optimize (minimize or maximize) some objective functions concurrently. The common multi-objective delinquent of WDS considered five parameters, including hydraulic capacity, water quality, flexibility (the system can be expanded with the increase in population), physical integrity, and cost of the system (Cheung et al. 2003). The purpose of most common multi-objective problems is to maximize the hydraulic benefit and minimize the cost of the network. The application of the multi-objective optimization of WDS is described in the next section.

Insert Figure 5 here

Many studies have been conducted on optimal design: minimizing cost, planning, and the operation of the network (Herstein et al. 2009; Hare et al. 2013). Most of the previous studies have focused on network piping systems (Prosser et al. 2013). At the same time, a small number of studies have simultaneously measured the real size of the network, the tank size, pump
scheduling, multiple operating conditions, and the demand variations (Coelho et al. 2014). Table 4 presents a summary of these previous studies which have applied multi-objective optimization to identify the optimal design of WDSs.

There are three possible stages of network optimization which can be employed over a life cycle, including deterministic, non-gradient, and real-time optimization (Dandy et al. 1996). Empirical algorithms, such as genetic algorithms and frog leaping algorithms, are some of the optimization methodologies which have been successfully used in the past (Savic et al. 1997; Dandy et al. 2008; Simpson et al. 1994; Maier et al. 2013).

Over the last three decades, several methods have been developed for the optimal design of WDSs. These optimization methods were based on single and multi-objective genetic algorithms (SOGA, MOGA) which have been used to improve water quality, minimize construction costs and extend the life of the network (Dandy et al. 2008; Zheng et al. 2011). Other algorithms, such as the non-dominated sorting genetic algorithm II (NSGAII), and the strength Pareto evolutionary algorithm II (SPEA2) have also been used in some studies (Fonseca et al. 1993; Deb et al. 2002; Zitzler et al. 2001). Usually, the cost has been considered as a single object in the construction and operation of WDS (Simpson et al. 1994). Recent studies have shown that network reliability should also be considered, in addition to cost, in the sustainability of WDSs (Atiquzzamane et al. 2006; Jourdan et al. 2005; Kurek et al. 2013; Raziyeh et al. 2007).

Most of the studies described in Table 4 applied optimization to either small or hypothetical WDSs. A small number of the above studies considered an integrated approach for overall optimization taking into consideration all of the relevant parameters, including water quality, optimal pump pressure (head), storage sizing, pipe sizes, embodied energy, pumping energy, GHG emissions, and the cost of a large complex actual network. Additionally, a few studies have pointed out that climate change and environmental factors should be taken into consideration as an objective function in addition to other optimization methods. Previous studies have used multi-objective optimization techniques for the sustainable design of WDS considering both the costs and the embodied energy (Dandy et al. 2008; Filion et al. 2004; Herstein et al. 2011; Piratla et al. 2012; Prosser et al. 2015; Mo et al. 2010; Wu et al. 2010; Roshani et al. 2012).

Dandy et al. (2006 and 2008) employed the multi-objective optimization technique for the sustainability of a WDS in New South Wales, Australia by considering cost, embodied energy, and GHG emissions. The results showed that 8% of integrated energy was saved, along with the
benefit of reduced GHG emissions. Figure 6 shows the comparison between the existing and the optimized WDS proposed by Dandy et al. (2006). The optimization of WDSs is a challenging task in which a tradeoff is required among these factors: economic, environmental, hydraulic reliability, energy, construction, and operation costs (Wu et al. 2010; Prosser et al. 2013).

4.2 Control Systems

4.2.1 Pumping system

According to the U.S. Department of Energy (2004), electric motors used for water pumping systems use 20% of the world's total energy (Coelho et al. 2014). In a municipal distribution system about 75% of the total electricity cost is related to water processing (Goldstein et al. 2002). Incorrect pump selection and inefficient pumping schedules are the most common problems associated with water pumping systems that lead to high energy costs. Therefore, pumping systems need to be optimized by optimal schedule computation and optimal pump combinations. Some of the studies show that the replacement of inefficient pumps can save up to 30% of energy costs (Gellings 2009).

Most of the past studies on optimal pump scheduling were conducted on FSPs and VSPs. In some cases, time has also been considered as a variable in the optimization process (Feldman 2009; Ormsbee 2009). Pumping is done either through direct (pump scheduling) or indirect (storage trigger level) operations. Pump scheduling is used to control the scheduled status speed of the pumps, while the trigger level is used to monitor the storage level (Stokes et al. 2014). With the help of pump scheduling, i.e., storage trigger level information and hydraulic simulation, the pumping operational energy consumption can be calculated. A more accurate estimation can be achieved by considering multiple operational scenarios for WSS (Stokes et al. 2014).

Nature-based algorithms have been used in more studies than gradient-based optimization as they do not require any simplification of problems (Cembrano et al. 1988). In the last few decades, many studies have combined local and global techniques to develop meta-heuristic optimization algorithms for improving the convergence of several methods (Brion et al. 1991; Mackle et al. 1995; Savic et al. 1997). Brion et al. (1991) presented well-cited examples of successful applications of classic algorithms in pump schedule optimization. Previously,
Cembrano et al. (1988) used the single objective technique to test the Conjugate Gradient in the Barcelona water network model in Spain. They selected the decision variables, like the flow combination from pumping stations and the optimal flow control by valves, in their study. Although they were successful in reducing the operational costs related to pump scheduling and optimal valve control, high computational efforts were required for analysis.

Brion and Mays (1991) applied KYPIPE computer programming to optimize the Austin (Texas) network. They used a generalized Gradient algorithm and Lagrangian methods to optimize the timing of the pump schedule. They found that about 17% of the operational cost can be saved by this optimization method. Later, a similar study performed by Coelho et al. (2012) found that the algorithm used by Brion and Mays (1991) was sensitive to the Lagrangian coefficients. Curi et al. (2012) conducted a study on a distribution system located in Campina Grande, Brazil using linear integer programming optimization methods. They optimized energy for three pumping stations and obtained an estimated 15% savings in energy costs.

Many researchers have used Genetic Algorithms (GA) in their studies of the pump scheduling optimization of water networks and have obtained positive results. To optimize the pump operational energy cost, Atkinson et al. (2000) and Van Zyl et al. (2004) studied the Richmond benchmark network with applied GA and a hydraulic simulator and found that the operational cost can be reduced by up to 19%. However, it was found that the GA computational time was high because of the hydraulic simulator. Later, Van Zyl et al. (2004) developed a hybrid optimization model by combining GA with two hill climber methods i.e., the Fibonacci Coordinate Search and the Hooke Jeeves Search optimization method. The optimization variables were defined w.r.t. tank level controls. The hybrid GA based methodology was applied to a WSS in Richmond, U.K. and achieved an estimated 25% reduction in the operational cost of pumping (Coelho, et al. 2014). However, they faced a problem in deciding whether to change from GA to the hill-climber-method during the optimization process. It was observed that the hybrid GA produced more reliable results than the pure GA method.

Wang et al. (2009) applied the GA method to minimize cost, the number of switches, and the total work time of a groundwater pumping system. Pump time interval optimization was performed by using a real number array as an alternative to a binary bit string. The methodology provided a number of solutions like low electricity cost at the same time as eco-aware pump schedules. However, it was observed that the algorithm convergence speed can be further
Shihu Shu et al. (2010) used a hybrid GA on a large WSS in China and found substantial reductions in the cost of pumping electricity (about 6%) and the water production cost. Lopez-Ibanez et al. (2008) proposed a parallel Ant Colony Optimization (ACO) method, combined with the EPANET library and applied to the Richmond benchmark network. They found that the parallel ACO method required half the computational time to produce better results compared to other sequential ACO techniques. They also analyzed the case study conducted by Van Zyl et al. (2004) by using a multi-objective approach and combining a second version of the strength pareto evolutionary algorithm (SPEA2) with EPANET 2.0 to reduce both cost and the number of pump switches. These results verified that by considering the binary encoding of the decision variables, i.e., tank water level and nodal pressure, better results were obtained when compared to the same problem solved by single objective optimization using any evolutionary algorithm.

There are various multi-objective optimization evolutionary algorithms (MOEA) like Niched Pareto (NPGA), Non-Dominated Sorting (NSGA), and Strength Pareto (SPEA) genetic algorithms used for the operational optimization of water networks. These MOEAs were used to find the optimal solution to minimize energy cost, pump scheduling, power peak time, and water tank level (Lüken et al. 2004; Coelho et al. 2012). Figure 7 shows the percentage of energy cost savings achieved in past studies (Modified from Coelho et al. 2014).

Figure 7 shows the hybrid GA (Fibonacci, Hooke-Jeeves, Search Pattern Method) resulted in more energy cost savings when compared to other computational methods. However, the study only considered a single objective optimization i.e., the maximum water “tank level”. Rao et al. (2007) developed a methodology based on an artificial neural network (ANN) to predict the best combination (starting conditions and demand) of different pumps and valve control settings. Later, the methodology was applied to reduce the pumping cost by 15 to 25% for a WDS in Haifa (Israel) and Valencia (Spain). However, the operational optimizing methodologies of these pumps cannot be applied to a large complex network due to the high computational time. A super-efficient supercomputer system is needed to solve the algorithms and to save the analysis duration. Hence, there is an advantage to using a combination of algorithms rather than the single objective (SO) algorithms. Table 5 illustrates a summary of the previous studies on the optimization of pumping systems and their limitations.
Coelho et al. (2014) studied and applied two genetic algorithms to optimize the water pumping energy, with an objective function to minimize cost, of two different urban WDSs. The applied evaluation algorithms were named the gradient-based Levenberg-Marquardt (LM) and the Evolutionary Algorithm (based natural evolution). Subsequently, the optimized mathematical model was integrated with EPANET to simulate two networks, including a basic network with an open loop and closed loop networks. The optimized results obtained by applying both the Levenberg-Marquardt algorithm (LM) and the Evolutionary algorithm (EA). It was observed that the LM method is more time efficient than the EA. However, the methodology presented by Coelho (2014) is applicable to elementary and small networks. They did not consider the energy production methods, the wasted energy, and the GHG emissions, neither did they apply the methodology to an actual WDS. Therefore, further research on a multi-objective (min. cost, min GHG, and max hydraulic benefits) optimization study for large-sized networks is still required.

4.2.2 Multi-objective Optimization

In pump operational optimization, it is important to consider other associated parameters like pump electrical energy saving, the source of energy generation (hydel or thermal), GHG emissions, and the total cost of the system. Wu et al. (2012) used MOGA for optimizing the total economic cost, pumping energy, and GHG emissions. Also, they investigated the impact of VSPs on their optimization results. This method was incorporated with VSPs in the conceptual design and the planning of WDS. They compared the optimization results of both VSPs and FSPs and observed that the cost of the network, the pumping energy, and the GHG emissions were lower in the case of VSPs than with the FSPs, as shown in Figure 8. Later, the proposed methodology was applied to a small network serving a population of fewer than 1,000 inhabitants. However, FSPs are preferred over VSPs for the optimization of large WDSs. Hence, there is a trade-off between pump replacement, capital cost, loss of efficiency due to water leakage, and associated GHG emissions. These parameters should be considered in the future studies of the optimization of WDS.

Richardson and Hodkiewicz (2011) studied the similar tradeoffs between costs and GHG. They investigated pump scheduling, including pipe size, but they did not consider the selection of pump type in their study. Some studies have used the multi-objective optimization of pump...
scheduling and suggested a trade-off between the construction of new water tanks and pump operational GHG emissions (Kang et al. 2012; Marchi et al. 2012). Wu et al. (2010) used trigger levels and optimized the pump operation for 24 hours, while Marchi et al. (2012) used both trigger and pump scheduling to optimize the operational energy. Both studies concluded that pump type selection and operational management options may lead to a reduction in energy and associated GHG emissions.

Ertin et al. (2001) and Ramos et al. (2011) compared energy efficiency for both pump scheduling and trigger levels. Ramos et al. (2011) concluded that the total operational energy has no effect on the pump schedule. They found that pump operational energy and GHG emission can be reduced by pumping water at off-peak loads. Ertin et al. (2001) found that 1% of energy can be saved by pump scheduling instead of using the storage tank trigger level. However, neither of the studies considered the time dependent operational and emission factors, such as the scheduling of pumps at low energy tariffs. A study by Stokes et al. (2014) considered the time-dependent emission factors (EFs) to calculate the pumping operational energy, and the associated environmental emissions. Other studies also used time-dependent emission factors (Roshani et al. 2012; Wu et al. 2012). Table 6 summarizes some recent studies on optimization used in multi objective approaches to minimize the cost, operational energy, and GHG emissions in WDSs.

**Insert Table 6 here**

The use of a control system in the pumping operation management system can save energy and further reduce GHG emissions (Stokes et al. 2014). However, multi-objective optimization considering all the influencing parameters in a large WDS is certainly a challenging task, i.e., minimizing the cost, the operational energy and the GHG emissions, and maximizing the hydraulic reliability and water quality in a large real water network. While preventing water losses via leakage through pressure management, the water pumping input energy can also be optimized (Boulos et al. 2010). However, a minimum amount of energy is needed for a pumping system to maintain a level of service pressure to the customer located at the highest point in the system.

### 4.2.3 Energy efficient control system

To reduce the GHG emissions and the amount of energy used, water utilities are adopting energy efficient water monitoring and delivery systems. Automation technologies have been used to
monitor the consumption of water resources and control water head (pump pressure), flow control (velocity), and water demand (Berry et al. 2007). In a distribution network, an efficient electro-mechanical control system can maintain an optimal pressure head, balanced flow rate, water demand variations, and relevant variables to conserve energy. A control system can: i) automatically increase the flow rate (on-demand basis); ii) reduce interruption, and prevent pump congestion resulting in decreased GHG emissions (Fetyan et al. 2007). Around 40% of pump operational energy can be saved by using an energy efficient drive instead of a water flow control valve (Kiselychnyk et al. 2009).

Energy efficient control systems can regulate both the pumping operations and chlorine boosters. These pumping control systems are integrated with programmable logic control (PLC), supervisory and data acquisition systems (SCADA), and wireless sensors (Kiselychnyk et al. 2009; Cembrano et al. 2000). However, utilization of these control systems might be restricted in complex WDSs, where the shape of a network changes both temporally and spatially due to an increase in water demand and a growing population.

To provide sufficient head (pressure), an energy efficient centrifugal pump coupled with an induction motor is used to deliver the required flow rate to its consumers (EPA 2014). A frequency-controlled induction drive is used to rotate the centrifugal pump, adjust the pressure (head) and the velocity based on the optimum criteria to meet customer needs. This can save up to 27% of electrical energy without altering the pump’s efficiency (Fetyan et al. 2007). However, induction motor-controlled pumps are not suitable for WDSs in hilly areas where pressure variations are quite frequent. In hilly areas, inverter-controlled parallel pumps have been used (Nakazawa et al. 2005). Siemens, ASEA Brown Boveri (ABB), Grundfos, and Pumpenfabrik Ernst Vogel GmbH have developed numerous energy efficient intelligent controllers to optimize pumping systems in WDSs (Kiselychnyk et al. 2009). The important characteristics of these control systems are summarized in Table 7. Most modern water utilities are currently using energy efficient water monitoring systems. In addition to water delivery, head loss reduction, flow control, and other features of this monitoring system also promote energy and water saving awareness to their customers and continuously monitor the consumption of natural water resources (Boulos et al. 2010). However, most of these water monitoring and controlling devices are expensive and need regular preventive maintenance to operate at optimal levels.

Insert Table 7 here
4.3 Renewable Energy Use for Water Pumping

A massive amount of CO\textsubscript{2} emissions is linked with the power used in WSS, which include water withdrawals, extraction, distribution and treatment. The electricity used by a water pumping system is usually generated by coal fired, natural gas, and diesel power plants. These power generation methods produce massive levels of GHG emissions (Stokes et al. 2014). Around the world, about 10 gigatonnes of CO\textsubscript{2} are emitted by electrical power generation, which is about 38\% of global emissions (World Nuclear Association 2012). In the last two decades, more attention has been given to renewable energy resources for electricity production with an aim to reduce GHG emissions. Countries all over the world are investigating the use of environmentally friendly energy generation systems to reduce CO\textsubscript{2} emissions in accordance with international obligations as agreed in the Kyoto Protocol at the United Nations climate change conference (Ramos et al. 2011). In urban WSSs, three common renewable resources i) solar, ii) wind, iii) water turbine/pump as turbine, have been used as alternative energy sources for water pumping (Ramos et al. 2011). However, the capital cost, initial investment and payback period for these systems are still high.

Pump as a turbine (PAT) is being used to convert excess hydraulic energy, i.e., the potential energy due to large head differences that exists in pipes into electricity (Ramos et al. 2011; Caxaria et al. 2011; Carravetta et al. 2014; Fontana et al. 2012; Lopes et al. 2006). It has been found that PAT can produce 5 to 100 kW of energy with approximately 85\% efficiency (Ramos et al. 2011). However, the system performance depends on flow rate and needs a large head difference between the higher and lower ends of the water mains (Caxaria et al. 2011). The study lead by Lopes et al. (2006) verified that the use of pump as a turbine in water mains can produce 4 kW of energy with a payback period of between 4 and 22 months for a small distribution system. Similarly, an experimental study was conducted by Fontana et al. (2012) in the city of Naples, Italy, where the WDS used pump as a turbine system, instead of pressure reducing valves to control losses, in addition to using it for electricity production.

Later, Coelho et al. (2014) used the same model and applied GA to find the optimal location of pressure control valves to minimize water losses and consequently energy savings. Ramos et al. (2008) proposed a framework to use PAT system for power generation in the city of Aveiro, Portugal. They found an optimal model that is cost effective and energy efficient with minimal GHG emissions. In normal water pumping operations, parameters like flow, head, and speed
show positive hydraulic values, while the same capacity pump used as a turbine shows a negative hydraulic value. This drawback was demonstrated by Ramos et al. (2011).

Mechanically coupled wind turbines have been used to extract and deliver water for many decades. Recently, small wind turbines with integrated energy were used for water pumping in small WDSs. The main advantage of wind turbine power generation is the independence of pumping locations, while its efficiency depends on the characteristics of its motors and pumps (Mathew et al. 2002). Rehman et al. (2012) conducted an experimental study in remotely located villages in Saudi Arabia on electricity generation using wind power. These villages were not connected with the national electricity grid. They found that a pump can deliver about 30,000 m³ of water per year from a depth of 50 m. A 2.5 kW wind-turbine was used ranging from 15m to 40m with an estimated operational pumping cost of 0.0128 US$/m³. However, the annual pumping cost of a wind turbine is still on the higher side compared to other alternative energy sources.

Photovoltaic (PV) cells are another renewable energy technology which has been used for water pumping in WSSs (Betka et al. 2005; Bouzeria et al. 2014; Vongmanee et al. 2005). Past studies concluded that an optimal PV pumping water system is only feasible if the PV generator values match the pump’s power requirement (Kolhe et al. 2004). However, a PV power system requires a large space and long hours of annual sunshine, which limits its application in some areas (Kiselychnyk et al. 2009). Among all environment-friendly renewable energy systems, the use of micro-water turbines in pipes to produce electricity and control pressure has been found to be the most feasible option with minimum associated GHG emissions (Ramos et al. 2011).

### 4.3.1 An example of small water utility (Lisbon, Portugal)

Ramos et al. (2011) proposed a sustainable hybrid solution to improve energy and hydraulic efficiency for a small district metering area (DMA) in the county of Lisbon, Portugal. The county of Lisbon, located in a hilly coastal area of Portugal, has a population of around half a million (Wikipedia 2017). The small DMA consists of a water source located on a hill at an elevation of 130 m above the mean sea level, which supplies water to two villages. One of the villages is located lower than the source (at an elevation of 17m) while the other is located at a height of 177m, i.e., higher than the source. The water is supplied to the upper and lower villages through pipes connected to tanks with 1780 m³ and 2025 m³ capacities, respectively. Consequently, water is supplied by pumping to the upper village, while a gravity system is
effective for the lower village. The significant available potential energy (head) in the case of the lower village is controlled with the help of a pressure reduction valve to prevent leakage.

In Portugal, about 40% of electricity is produced by fossil fuels resulting in higher GHG emissions (Redes de Confiança, REN 2010). The remaining electricity is generated through hydropower, wind, and other renewable resources. Ramos et al. (2011) conducted a study on two small Portuguese villages (population less than 10,000) to optimize a water pumping system. Electricity data was obtained from the Portuguese power companies to optimize water pumping for the two villages. In the first option, turbine was connected (to the lower village’s tank) with pipes to replace the pressure reducing valves. In the second option, shown in Figure 9, wind turbine integrated power was used to operate the second pump (to fill the upper village’s tank) and a water turbine system was used to generate electricity for the lower village.

**Insert Figure 9 here**

A water turbine was installed in the gravity pipe of the lower tank to utilize the potential energy available in the pipe. About 520 kWh/day of electricity is produced by a hydropower plant which emits a corresponding 5.1 kg of CO₂ (Hydro-Québec 2001). On the other hand, an equivalent level of energy produced by fossil fuels (petrol, gas, coal) emits around 442 kg CO₂. A 30 kW wind turbine FL30 (2017) is integrated with the main grid system, which results in reduced electricity consumption from the main grid and about half of the CO₂ emissions. Figure 10 shows the power generation with pump as a turbine and wind energy pumping water (normal, summer, and winter), respectively, and the corresponding CO₂ emissions in the system. However, the methodology proposed by Ramos et al. (2011) has some limitations. In Lisbon County, both the water and electricity supply load values remained the same during peak hourly demand. It was suggested that the pumping energy could be reduced during off-peak electricity tariffs (night time) which is not possible. Pump, as a turbine system is the only suitable solution to replace PRVs valves if the hydraulic potential energy is available in the pipes. Although wind power generation has no CO₂ emissions, the initial cost of windmills is high in comparison to hydropower when used to obtain the same amount of energy.

**Insert Figure 10 (a, b) here**
4.4 Sustainability of Water Distribution System

4.4.1 Life Cycle Assessment

Life cycle assessment (LCA) is a procedure to estimate the performance of an entire system by considering a ‘cradle-to-grave’ approach (Nair et al. 2014; SAIC 2006). LCA serves as a useful information tool to examine future substitution scenarios for strategic planning and decisions (Sadiq et al. 2006). Assessment of the system starts with the extraction of raw material, followed by design and manufacturing, eventually culminating in its return to earth (Hendrickson et al. 2014). Figure 11 shows the typical life cycle phases of a WDS from raw material to the end of its life. LCA has been applied to water technology assessment for nearly three decades (Loubet et al. 2014).

Most of the past studies on water and wastewater life cycles are related to treatment processes (Emmerson et al. 1995; Jeong, et al. 2015). Since 2005, a number of LCA studies have investigated the various life cycle stages of WDS, including pipe manufacturing, pipe repairing and replacement, environmental factors, water recycling, embodied energy related to water leakage, and the operational energy requisite to run a distribution system (Du et al. 2012; Herstein et al. 2009; Loubet et al. 2014; MacLeod et al. 2012; Nault et al. 2015). The traditional studies of WDS LCAs have focused on the comparison of different pipe materials which evaluated the sustainability of WDSs and assessed the future implications of present decisions (Nault et al. 2015). The sustainability of a WDS can be assessed using a triple-bottom-line approach which is based on three main dimensions, i.e., economic, social, and the environmental (Gleick 1994). Due to the aging of infrastructure, an enormous amount of investment for rehabilitation, replacement, and expansion is required in each step of the life cycle stages of WDSs (Friedrich et al. 2002; Lundie et al. 2004; Raluy et. al 2005; SAIC 2006; Foley et al. 2010).

Insert Figure 11 here

Recent research focused on LCA has considered not only the economic aspects but also the environmental factors of WDS (Hendrickson et al. 2014). Dennison et al. (1999) used LCA for a plastic-vinyl-chloride (PVC) and steel-iron pipes. They concluded that an enormous amount of energy was consumed during the pipe manufacturing processes. An LCA study was conducted by Lundie et al. (2004) on a WDS in Sydney, Australia. They forecasted the future water management planning for the city in respect of population growth, expansion of infrastructure,
demand, and GHG emissions. Filion et al. (2004) computed the lifecycle energy analysis (LCEA) of WDSs and studied its sustainability. The proposed LCA methodology was based on an economic-input-output (EIO) model developed by Carnegie University (Carnegie Mellon University, 2012). They estimated the embodied energy linked with pipe manufacturing (from raw material to its disposal) and the operational energy required for a water pumping system. Stokes et al. (2006) used a similar framework to the one proposed by Filion et al. (2004) and evaluated alternative solutions for drinking water supplies. An index-based LCA model developed by Herstein et al. (2009) was used to assess the eco-friendly impacts of expanding and operating WDSs. The results revealed that the absence of a lifecycle energy perspective would lead to erroneous estimations for the energy and the environmental impacts.

Although all of these studies endorsed the usefulness of LCA, most of them were conducted using hypothetical models, while some of them focused on the rehabilitation or replacement (R&R) of water mains and the optimization of pumping systems in a real-time WDS (Filion et al. 2004; Wu et al. 2008). Due to rising energy prices and GHG emissions, water utilities are striving to optimize energy usage in each stage of the WDS. In the following sub-sections, LCA energy perspective models are reviewed in detail to investigate the environmental impacts, GHG emissions, pipe manufacturing energy, replacement (embodied) energy, and the disposal energy of a WDS.

4.4.2 Life Cycle Energy Analysis

Many water utilities are striving to reduce energy cost and environmental emissions through lifecycle energy analysis (LCEA) of WDSs (Herstein et al. 2011). The LCEA of WDS has received more attention in the last decade. The LCEA study includes the embodied energy of pipe manufacturing, disposal energy, pump operational energy, the energy required to overcome friction losses in pipes, and reductions in the GHG emissions of the system (Du et al. 2012). The LCEA tool computes the energy used in each step of a WDS rather than considering the whole life cycle of the system (Nair et al. 2014). LCEA methodology needs fewer data requirements and less calculation effort than a normal LCA computation (Prosser et al. 2013). Figure 12 shows the use of energy and the associated GHG releases during the LCA phases of a WDS (Nault et al. 2015).

Insert Figure 12 here

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In WDS, the environmental effects, such as atmospheric emissions, water pollution, global warming potential (GWP), and energy consumption, can be analyzed together with an LCA approach (Nair et al. 2014). Various studies have investigated and developed environmental indices with respect to energy consumption in urban water systems. Several advantages of an LCA are grouped together in a stand alone index that helps to categorize the effects instigated by a separate system on the environment (Nair et al. 2014). Herstein et al. (2009) used this LCA approach to investigate the eco-friendly effect with respect to pipe repair and replacement of a large WDS. Later this index was integrated with other WDS optimization methods to provide cost effective and environmentally friendly solutions. The study showed that the operational energy used in WDS has an important role in deciding the eco-friendly sustainability of the system. However, to obtain the environmental data from each step of an LCA is a daunting task (Landu et al. 2007).

According to Zakkour et al. (2002), energy contributes a substantial impact on GHG emissions in WDS. Therefore, a full LCA is not required to investigate eco-friendly related impacts other than energy, especially in a WDS. Filion et al. (2004) also supported this idea and used the LCEA approach rather than investigate the whole LCA of the system. However, the study did not consider the energy required during pipe installation, maintenance, and pipe cleaning. Later, Dandy et al. (2008) applied genetic algorithms in their study to evaluate a two reservoir level in a WDS. Their study calculated a pareto optimal solution to find the minimum costs and embodied the energy of two types of PVC pipes. In their case study, the pumping energy of the network was not taken into account. In the network, water was distributed from reservoirs at a higher elevation to the lower end by gravitational force. However, pumping energy is required in a flat ground area where the source end users are on the same elevation.

Mo et al. (2010) developed an EIO-LCA model and estimated the embodied energy linked with the infrastructure of a WDS. Later, the same methodology was applied to the WDS in the city of Kalamazoo, Michigan, in the USA. The city consumed around 9.3 MJ/m$^3$ of energy, and about 25-30% of the total was utilized for treatment purposes. The study presented a comprehensive model with inadequate information on operational energy estimation.

Herstein and Filion (2011) performed an LCA study on the optimized R&R planning of deteriorated pipes. They observed that significant savings can be achieved in the capacity of embodied and operational energy by reducing leakage and friction losses. The study found that
capital cost is directly linked to pumping operational energy, regardless of the pipe replacement plan. However, the environmental index (EI) calculated by Herstein et al. (2009) did not obtain optimized results when combined with the EIO-LCA of the system. Prosser et al. (2013) extended the work of both Filion et al. (2004) and Herstein et al. (2009). They further performed an embodied energy analysis of pipe manufacturing and the operational life cycle stages of a WDS. They proposed various schemes for pipe replacement planning. In their analysis the pumping energy was compared with the embodied energy associated with the pipe replacement of the system. Outcomes of the study revealed that by using an effective water mains replacement plan (i.e., asset management), substantial energy can be saved.

More than 30 studies on the LCA of WDS were reviewed in this paper. These studies were primarily focused on environmental impacts with respect to pipe manufacturing, repair and replacement, leakage, buried pipe disposal, infrastructure construction, pumping operation, pump manufacturing and renovation (Amores et al. 2013; Dandy et al. 2008; Filion et al. 2004; Friedrich et al. 2009; Godskesen et al. 2011; Herstein et al. 2011; Lundie et al. 2004; Prosser et al. 2013; Remy and Jekel 2011; Venkatesh et al. 2014; Wu et al. 2010; Feifei et al. 2011; Hendrickson et al. 2014; Slagstad et al. 2014; Loubet et al. 2014; Nault et al. 2015). Figure 13 summarizes the types of past studies on the LCA of WDS. About 53% of the studies evaluated the impact of the construction and operations of pipe infrastructure, while only 3% addressed the issues associated with pump manufacturing and renovations, as shown in Figure 13. In general, most of the LCEA studies reported in the literature have ignored the geographical, social, and economic characteristics of large-sized WDSs.

**Insert Figure 13 here**

General system analysis (GSA) is another methodology used for environmental impact assessment of the network. GSA can evaluate the functions of the entire network, while LCA analysis ignores the social aspects of the system (Balkema et al. 2002). Although LCA is a widespread assessment tool and can evaluate individual aspects, as well as whole networks, its application has been limited thus far to normal centralized systems rather than decentralized systems. Integrating LCA with GSA can provide more insights concerning the water energy nexus (WEN) of a drinking WSS. Table 8 summarizes past LCEA studies of urban WDS (Loubet et al. 2014).

**Insert Table 8 here**
The studies described in Table 8 primarily investigated the life cycle stages of pipe construction and the operation components of WDS, while less attention was paid to energy consumption in civil construction works (e.g., excavation), human health, ecosystem quality, and water resources. To elaborate further about the LCA (energy perspective) of a WDS, a case study presented by Prosser et al. (2013) is discussed in the following section.

4.4.3 An example of the Midwestern USA

Prosser et al. (2013) developed a LCEA methodology for a WDS to integrate embodied energy with repair and replacement (R&R) planning of deteriorated pipes and proposed various energy savings solutions. The proposed framework investigated the energy lost due to leakage and pipe friction energy, and calculated its payback period. The LCEA was applied to a real WDS serving 1 million consumers located in the midwestern region of the United States. The water utility supplied 530,000 m³/day of water through 28 pumping stations, 3 water treatment plants, and around 6000 km of transmissions and distribution mains. The terrain of the area is a combination of hilly and flat land.

The cradle to grave analysis was completed using an EIO-LCA method which was developed by Carnegie university (Carnegie Mellon University 2012). It was found that water mains, consisting of 140,000 individual pipe segments, hold the largest share of the total embodied energy (Filion et al. 2004). For an analysis, a hydraulic model with a pump was created to compute the pumping energy of the system. Similarly, the embodied energy data linked with the pipe replacement was obtained from the city of Toronto (Canada) water authority (Racoviceanu et al. 2007). The historic (since 1969) pipe data were grouped according to the type of pipe material, diameter, and age. Most of the steel and plastic material pipes were 5 to 60 years old; however, pipes up to 150 years of age were also found to be operational in some locations. The developed LCEA methodology considered the pipe manufacturing and operational embodied energy linked with the life cycle stages of pipe R&R. Three R&R schemes referred to as A, B, and C for the period between 2020 and 2070 were proposed. The proposed scheme “C” was based on the age of the water mains, while “A” and “B” were based on the pipe rupture rate. For an initial time step of 2020, 11% water loss (as reported by a partner utility) was assumed for all the scenarios. Three types of leakage data (reported, unreported, and instance) were analyzed, and with minor modification, the leakage event was modeled. The amount of water energy lost...
due to natural disasters, such as an earthquake, or burst pipes from large water mains was excluded from this study.

It was estimated that the embodied energy linked with pipe R&R is the same as the embodied energy required for manufacturing new pipes. Only the embodied energy linked with new pipe manufacturing was calculated. For old pipes, if the repair time (linked with embodied energy) was longer than three days, it could be used as landfill or for other recycling purposes. Other energy linked with pipe production and transportation was not counted in this study. EPANET software simulations were performed to estimate the pumping energy consumption and assumed that the pump worked at about 70% of its efficiency (HydraTek 2013). In order to evaluate the impact of pipe roughness on pumping energy, both a fixed and a variable Hazen-Williams constant “C” factor was used. A roughness coefficient “C” value of between 120-130 was taken for each replacement plan. It was estimated that about 47.3 kWh/MG embodied energy was lost to treated water due to leakage in the WDS (Racoviceanu et al. 2007). The results in Figure 14 (a, b) show a summary of the anticipated outflow volume and the allied embodied energy lost in all planning phases of the system. The results also show that, at the end of the 2070 forecasting period, all pipe changing plans can save a huge amount of embodied energy which was previously lost in the system due to leakage.

The analysis shows that energy can be saved through pipe replacement, leakage reduction, and by improving pumping efficiency. About 33% of operational energy can be saved by controlling water leakage (no pipe replacement plan). The analytical results show that efforts made on water leakage detection have a lower impact on energy saving than the impact of improving the pump efficiency of the system. If pump efficiency improves from 60 to 80%, around 33% of operational energy will be saved for all plans A, B, C, w.r.t. reference base-point. Figure 15 (a,b,c,d) shows the annual operational energy with and without pipe replacement, the embodied energy, % of energy saving, and the payback period for each plan. Results demonstrated in Figure 15 (c) show that the embodied energy linked with pipe changing has more weight when compared to the percent of operational energy required to drive a complex WDS.
The results in Figure 15 (b) show that, in the first 10 years of 2020, about 4.9-6.4 million kWh of operational energy was saved through leakage reduction.

However, to achieve this energy saving the utility needs to pay the infrastructure construction cost linked with pipe replacement. This is about 80 million kWh for plan “C” and 112 million kWh for plan “A” in 2020, as described in Figure 15 (c). Figure 15 (d) shows the energy payback period for each plan. By the end of the first decade 2020, the cost invested in the form of embodied energy for Plan “A” will reduce the operational energy by 6.4 million kWh, as shown in Figure 15 (b). The data show that, as more as old pipes are replaced, the pumping energy system savings increase. The analytical results showed that the pipe replacement embodied energy is significant, regardless of whether an enormous amount of energy is required to run a large WDS. Interested readers can see the details in Prosser et al. (2013).

However, the LCEA study by Prosser et al. (2013) was only carried out for ductile iron pipes of the same diameter and made from the same materials. Various materials like PVC and asbestos cement pipes have different embodied energies linked with pipe manufacturing processes. The study also ignored the pipe rehabilitation procedure which can save time and cost. Further research is required on energy balance for pipe rehabilitation by using other materials for a complex WDS.

5 Summary, Conclusions, and Recommendations

5.1 Summary

All the components of a drinking WSS, including extraction from the source, treatment, and distribution to the end user, consistently consume energy. Globally, most of the energy is generated from fossil fuel sources, a part of which is utilized by WSS, resulting in more GHG emissions, climate change, and environmental pollution. The review of the literature has revealed that the WEN of drinkable WSS has received more attention in recent years due to an increase in energy usage and its effect on global warming.

The application of integrated WENs has become more popular due to climate change, population growth, and increasing energy crises. The above review of the research shows that most of the existing WDSs around the world were designed when electricity production costs and associated GHG emissions were not major issues. The energy used for public WDSs signifies that about 25% of the world’s urban energy can be saved through cost effective solutions (CEC 2005).
Most of the studies proposed water-energy saving solutions, like optimizing pumping power and
design of the network, and either repairing or replacing pipes through investment.
Watergy provides water-energy solutions through technical and managerial changes with little or
no investment, such as leakage prevention, and through educating the public to conserve tap
water. However, the Watergy application depends on local factors such as topography, water
demand, supply, culture, and electricity tariffs. A smaller number of studies report the
applications of Watergy solutions in large WDSs.
WDS design (pipe diameter) and pump operation (scheduling) optimization have been
investigated in the past to decrease both the operational energy cost and the associated
environmental pollution. Due to the complex nature of WDS, optimization problems can be
solved by using trial and error methods (Coelho et al. 2014). Some studies reported that the use
of a nonlinear (classical and heuristic) optimization algorithm is more effective and efficient to
improve the design and operation of WDS.
Many studies have been conducted on optimal design, minimizing cost, planning, and the
operation of the network, while other studies also considered network piping systems (Prosser et
al. 2013). However, fewer studies measured the real size of the network, the tank size, pump
scheduling, multiple operating conditions, and the demand variations, simultaneously. Numerous
studies reported in the literature reveal that pumping energy can be improved using variable-
speed-drive pumps (VSPs) rather than fixed-speed-drive pumps (FSPs). It was found in the
literature that, after refurbishing the WDS pumps, 11% of the pumps recovered their lost energy
efficiency (HydraTek 2013).
The energy-perspective LCA models have been reviewed in detail to investigate environmental
impacts, GHG emissions, energy used for pump operations, and the life cycle stages of pipe
manufacturing (embodied energy) in distribution networks. Some studies considered the LCA of
pipe repair or replacement (R & R) and operational optimization, but they did not account for the
energy associated with excavation, landfill, pipe transportation, and GHG emissions. However,
pipe manufacturing has an embodied energy which is linked with material production.
In the last two decades, more attention has been given to renewable energy resources for
electricity production with an aim to reduce GHG emissions. Very few studies have reported the
use of renewable energy resources, like wind, solar, and micro-hydro turbine, as an alternative
source of energy for water pumping.
5.2 Conclusions

Numerous studies have revealed that energy efficiency can be improved in all segments of a WDS by regular checks on the system, higher water pumping efficiency, in-conduit hydroelectricity, better leak management, infrastructure improvement, and system automation. Generally, in a large-sized WDS, where a continuous water head is required, fixed-speed pumps (FSPs) are preferred over variable-speed pumps (VSPs) for the optimization of large WDSs. VSPs are useful in networks where the water demand varies (closed pressure zones) and the pump size is not a deciding factor. Most of the reviewed studies suggest a trade-off between energy cost and the associated GHG emissions when selecting FSPs over VSPs for a large WDS.

Pumping in WDS is done either through direct (pump scheduling) or indirect (storage trigger level) operations. Most of the past studies on pump scheduling were conducted on fixed-speed pumps (FSPs). Therefore, the past studies suggested that pumping systems can be optimized by optimal schedule computation and by optimal pump combinations.

Many researchers have used genetic algorithms (GA) in their studies of pump scheduling optimization. They found that nature-based algorithms perform well when compared to gradient-based ones because they need less computational time. Some studies reviewed above used multi-objective optimization evolutionary algorithms (MOEA) to find the optimal solution to minimize energy cost and optimize pump scheduling, power peak time, and water tank levels. However, these pumps’ operational optimizing methodology cannot be applied to a large complex network due to their high computational time. A super-efficient supercomputer system is needed to solve the integrated MOEA simultaneously. Therefore, the advantage of using a combination of algorithms, rather than the single objective (SO), is reported in the literature.

5.3 Recommendations

The optimization of WDS alone is a challenging task. There are some constraints involved in the optimization of the network and a trade-off is suggested between hydraulic reliability, the environment, energy, and the cost of WDS. No perfect algorithm has been developed so far to solve all of the optimization problems in a large WDS. The optimal design of WDS still needs further exploration to cover all multi-objective parameters of a real and complex network.

Very few studies of pump optimization have considered GHG emissions with the pumping cost and operational energy of the system. Therefore, further research on a multi-objective (min. cost,
min GHG, and max. hydraulic benefits) optimization study for large-sized networks is still required.

The embodied energy associated with pipe manufacturing consumes more energy and produces more GHG emissions. Pipe repair is more cost effective than replacement and has fewer GHG emissions. However, the reviewed studies suggest a trade-off between pipe replacement and embodied energy. This review of the previous research shows that the embodied energy related to the water distribution infrastructure has not been adequately addressed so far.

The reviewed case studies showed that, among all of the conducted studies, the micro-hydro turbine (used in water mains) is the most feasible and cost effective, while also having less associated GHG emissions. However, the capital cost, initial investment and payback period for all these renewable energy systems are still relatively high. Therefore, it is recommended that future research should not only focus on cost, operational energy, and the optimized design of WDS, but also on the sources of electricity generation (renewable energy) in order to reduce GHG emissions.

Acknowledgments
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Fig. 1 Water-Energy-Nexus cycle (modified from Schaum et al. 2015)
Fig. 2: Review study framework of water-energy-nexus for WDSs
Fig. 3 Energy use in each step of drinking water system from source to end user (residential) in flat terrain (developed using data from EPA 2013)

Fig. 4 Water lost due to leakage in large WDSs (developed using data from Barry et al. 2007)
Fig. 5 Nonlinear optimization algorithms used in design of WDSs (Modified from Coelho et al. 2014)

Fig. 6 Comparison between original and proposed optimized WDS (developed using data from Dandy et al. 2006)
Fig. 7 Various evolutionary algorithms used for pump operational optimization of WDSs;
(Developed using data from Coelho et al. 2014)

*SO=Single Objective, MOEA=Multi Objective Evolutionary Algorithms, (SPEA)=Strength Pareto Evolutionary Algorithm, PSO= Particle Swarm Optimization, F.H.J= (Fibonacci, Hooke Jeeves, Pattern Search, NSGA=Non-Dominated Sorting Genetic Algorithm, LM= Levenberg-Marquardt, GSA= Genetic Simulation Annealing, LP= Linear programming
Fig. 8 Energy consumption and corresponding GHG emissions in: (a) Fixed speed pumping (b) Variable speed pumping (modified after from Wu et al. 2012)
Fig. 9 Combination of water-turbine and wind-power system used for water pumping in Portugal (modified after Ramos et al. 2011)
Fig. 10 (a) Electricity generated by Pump as Turbine (PAT), (b) With Wind Turbine; (developed using data from Ramos et al. 2011)
Fig. 11 Typical life cycle stages of WDS

Fig. 12 Life cycle stages, energy consumed, and GHG emissions
A few past LCA studies considered the environmental impact with respect to material extraction, construction and operation WDS (developed using data from Loubet et al. 2014; Nault et al. 2015)
Fig. 14 (a) lost volume due to leakage (b) energy lost due to leakage in all proposed plans (developed using data from Prosser et al. 2013)
Annual Operational Energy Baseline and Replacement Plans (millions kWhr)

(a) Years

(b) Annual Operational Energy Saving (Baseline-Replacement) 10^6 kWh

Plan A
Plan B
Plan C

(Baseline Scenario)
Fig. 15 (a) Annual Operational Energy in each Plan, (b) Operational Energy saving in each Plan, (c) Annual Embodied Energy in each Plan, (d) Payback Period of each Plan (developed using data from Prosser et al. 2013)
Table 1: An estimated energy use in urban drinking WDSs of various regions of the world

<table>
<thead>
<tr>
<th>Region</th>
<th>Activity</th>
<th>Energy consumed kWh/m³</th>
<th>*% of total State/City Energy consumed</th>
<th>**Equivalent CO₂ emission per of kWh energy (kg)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louden, Virginia, USA, small town, a mountain valley</td>
<td>Water distribution</td>
<td>2.28</td>
<td>1-2 % of the state</td>
<td>1.6</td>
<td>(Alanis 2009)</td>
</tr>
<tr>
<td>Alexandria-Virginia, USA, a flat terrain</td>
<td>Water distribution</td>
<td>0.55</td>
<td>--</td>
<td>0.38</td>
<td>(Alanis 2009)</td>
</tr>
<tr>
<td>Spain</td>
<td>Urban Water Distribution in general</td>
<td>0.12-0.22</td>
<td>--</td>
<td>0.15</td>
<td>(Joan Corominas 2009)</td>
</tr>
<tr>
<td>China</td>
<td>Urban Water Distribution in general</td>
<td>0.2-0.3</td>
<td>--</td>
<td>0.22</td>
<td>(Liu et al. 2013)</td>
</tr>
<tr>
<td>Toronto, Canada</td>
<td>Water Distribution</td>
<td>0.3-0.4</td>
<td>1-2 % of greater Toronto area</td>
<td>0.1</td>
<td>(Venkatesh et al. 2014)</td>
</tr>
<tr>
<td>Turin, Italy</td>
<td>Water distribution</td>
<td>0.3-0.32</td>
<td>-</td>
<td>0.2</td>
<td>(Venkatesh et al. 2014)</td>
</tr>
<tr>
<td>Lahore, Pakistan</td>
<td>Water distribution to residential area</td>
<td>0.5-0.62</td>
<td>1-2% of the total municipal energy</td>
<td>0.42</td>
<td>(Nasir 2015; Wakeel et al. 2016)</td>
</tr>
<tr>
<td>Melbourne, Australia</td>
<td>Urban Water Distribution</td>
<td>1 – 2</td>
<td>0.2-0.6 % of the total urban Energy</td>
<td>1.5</td>
<td>(Kenway et al. 2016)</td>
</tr>
<tr>
<td>Taipei, Taiwan</td>
<td>Urban Water Distribution</td>
<td>0.26-0.51</td>
<td>--</td>
<td>0.36</td>
<td>(Lee et al. 2017)</td>
</tr>
<tr>
<td>India</td>
<td>Urban Water Distribution in general</td>
<td>0.3-0.4</td>
<td>0.5-1% total urban energy</td>
<td>0.23</td>
<td>(Huang et al. 2018)</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>Urban Water Distribution in general</td>
<td>0.7-0.8</td>
<td>1-5% of eastern province energy</td>
<td>0.6</td>
<td>(Al-mutrafi et al. 2018)</td>
</tr>
</tbody>
</table>

*~* Data not available,

*The of energy consumption % age varies with different topographies, depth, volume, and the technology used

**The GHG emission ~ kWh energy (USEPA 2014)
<table>
<thead>
<tr>
<th>References</th>
<th>Description</th>
<th>Location</th>
<th>Size of system</th>
<th>Energy indicators</th>
<th>Lifecycle considerat ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Pelli and Hitz 2000)</td>
<td>Analyzed water quality, infrastructure, and pump efficiency</td>
<td>Sagno-Mendrisio Municipality, Switzerland</td>
<td>Small</td>
<td>* E1: Quantity Indicator =0.71 kWh/m³</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>* E2: Quality Indicator in relation to energy consumption =2.75</td>
<td></td>
</tr>
<tr>
<td>(Colombo and Karney 2002)</td>
<td>studied the link between water losses and energy costs</td>
<td>EPANET network model</td>
<td>Small</td>
<td>E3: Energy ratio as a function of leak detection, location, and magnitude About 30% of the system water lost – 0.6 kWh/m³ of energy</td>
<td>×</td>
</tr>
<tr>
<td>(Filion et al. 2004 and 2009)</td>
<td>Evaluated life cycle energy analysis (LCEA), pipe replacement and environmental impact of WDS</td>
<td>New York City primary water supply</td>
<td>Large</td>
<td>E4: Environmental impact Indicator associated with Pipe fabrication and its disposal energy A 100mm diameter pipe consume 80200 kWh/km manufacturing and 1400 kWh/km disposal energy</td>
<td>√</td>
</tr>
<tr>
<td>(Dandy et al. 2008)</td>
<td>Evaluated the embodied energy and environmental impact indicator, optimize the WDS design</td>
<td>Simple network model</td>
<td>small</td>
<td>E5: Embodied energy and environmental impact indicator, trade-off between cost and total energy for a simple WDS</td>
<td>√</td>
</tr>
<tr>
<td>(Cabrera et al. 2010)</td>
<td>Evaluated the performance indicators to assess the system from the energetic point of view</td>
<td>EPANET test model (later applied to real network)</td>
<td>Small</td>
<td>E6: Energy balance indicator (kWh/m³): Energy injected to the system to energy lost due friction and leakage</td>
<td>×</td>
</tr>
<tr>
<td>(Boulos et al. 2010)</td>
<td>Developed Water network energy efficiency (WNEE) tool</td>
<td>8 large cities WDSs of Europe</td>
<td>Large</td>
<td>E7: minimum level of service pressure indicator, optimize the power (kWh/m³) needed to convey water to each customer</td>
<td>×</td>
</tr>
<tr>
<td>(Bolognesi et al. 2014)</td>
<td>Proposed the concept of unavoidable minimum energy (UME) as the reference for defining an energy efficiency indicator for WDS</td>
<td>Cabrera et al. (2010) model adopted for this study</td>
<td>Small</td>
<td>E8: Unavoidable minimum energy indicator, maximize the energy efficiency w.r.t. pipe diameter (m), leakage rate, and pump energy (kWh/m³)</td>
<td>×</td>
</tr>
<tr>
<td>(Smith et al. 2016)</td>
<td>Evaluated the environmental emissions impact on urban WDS</td>
<td>China</td>
<td>Large</td>
<td>E9: Low carbon emission indicator; controlling leakage (less GHG emissions /unit volume of water: 0.213 kg-e CO₂/m³)</td>
<td>√</td>
</tr>
<tr>
<td>(Scanlan 2016)</td>
<td>Developed energy indicator, evaluated energy lost due to friction, leakage, and excess energy</td>
<td>Ontario, Canada</td>
<td>Large</td>
<td>E10: Energy indicators for WDS</td>
<td>×</td>
</tr>
</tbody>
</table>

--- Data is not given

a- Quantity Indicator (energy used to lift water/year) / (theoretical minimum energy consumption)
b- Quality Indicator (The ratio of actual energy used to the minimum energy required (< 2 Very Good, 2-3 Good, 3-4 Need Improvement)
<table>
<thead>
<tr>
<th>References</th>
<th>Study area and location</th>
<th>Energy saving methods</th>
<th>Population</th>
<th>Amount of Energy saved</th>
<th>* GHG reduction</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>California Energy Commission (CEC-2005)</td>
<td>State of California, U.S.A.</td>
<td>Replace pipes (increased diameter) overhaul pump’s impellers</td>
<td>39 million (2015)</td>
<td>880 million kWh/year (from water &amp; wastewater facilities)</td>
<td>618000 metric-ton CO₂</td>
<td>Pipe replacement cost is high</td>
</tr>
<tr>
<td>(Mass et al. 2010)</td>
<td>Province of Ontario, Canada</td>
<td>Pressure management and leak detection (0.68 kWh/m³ energy saved)</td>
<td>13.6 million (2014)</td>
<td>4.4 million kWh/year</td>
<td>3200 metric-ton CO₂</td>
<td>Infrastructure up-gradation pump repairing cost</td>
</tr>
<tr>
<td>(Ramos et al. 2011)</td>
<td>Lisbon county water utility, Portugal</td>
<td>In conduit water turbine installation for electricity generation</td>
<td>2.8 million (2015)</td>
<td>520 kWh/day energy saved</td>
<td>442 kg CO₂</td>
<td>assumes daily water consumption</td>
</tr>
<tr>
<td>(Frank R. Spellman 2013)</td>
<td>Chandler water utility, Arizona, U.S.A.</td>
<td>Optimize water storage tank, upgraded the pumps, maintain pressure zones</td>
<td>0.25 million (2014)</td>
<td>1.4 million kWh/year</td>
<td>996 metric-ton CO₂</td>
<td>additional equipment cost</td>
</tr>
<tr>
<td></td>
<td>Fortaleza Brazil WDS</td>
<td>Operational procedures improved and standardized retrofitting pumps and motors, optimizing the use of contracted demand Prevent leaking, controlled water supply, applying metering system</td>
<td>2.5 million (2015)</td>
<td>88 million kWh over four years</td>
<td>68 metric ton CO₂</td>
<td>Initial investment of $1.1 million Bringing water from the river 200 km away</td>
</tr>
<tr>
<td>Watergy, The Alliance to Save Energy (Barry et al. 2013)</td>
<td>Vishakhapatnam India WDS</td>
<td></td>
<td>1.7 million (2011)</td>
<td>1.4 million kWh/year</td>
<td>2400 metric ton CO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mogale City South Africa</td>
<td></td>
<td>0.3 million (2011)</td>
<td>15.4 million kWh/year</td>
<td>13,700 metric tonnes of CO₂</td>
<td>Small network, leakage rate high</td>
</tr>
<tr>
<td>(Craig. p. Aubuchon 2014)</td>
<td>Evansville water utility Indiana State, U.S.A.</td>
<td>Embedded energy in real water losses (about 475-million-gallon water leakage saved)</td>
<td>0.2 million (2014)</td>
<td>750 MWh/year</td>
<td>400-ton CO₂</td>
<td>Equipment installation cost</td>
</tr>
</tbody>
</table>

* GHG emission factor varies and depends upon the electricity generation methods (coal, gas, thermal and hydel)
### Table 4: Summary of the past studies used multi-objective optimization methods in design of WDSs

<table>
<thead>
<tr>
<th>References</th>
<th>Multi-objective Variables</th>
<th>Study parameters</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Kapelan et al. 2005)</td>
<td>cost of the pipes, head lost, minimum pressure</td>
<td>Systems design and Reliability</td>
<td>The methodology tested on New York Tunnels reinforcement problem only (data assumed)</td>
</tr>
<tr>
<td>(Dandy et al. 2008)</td>
<td>minimize cost, energy consumption, GHG emissions</td>
<td>optimum design sustainability objectives identified</td>
<td>Applicable for simple WDS for irrigation purpose not for populated complex WDS</td>
</tr>
<tr>
<td>(Wu et al. 2010)</td>
<td>minimize cost and GHG emissions</td>
<td>The impacts of minimizing GHG emissions on the results of WDS optimization</td>
<td>Hypothetical network model</td>
</tr>
<tr>
<td>(Fu et al. 2011)</td>
<td>minimization of total design cost and maximization of system performance (pressure, head)</td>
<td>provide the cost-effective and reliable design of WDS to cope up future uncertainties</td>
<td>Proposed methodology tested on the New York tunnels and Hanoi network only</td>
</tr>
<tr>
<td>(Lancy et al. 2012)</td>
<td>minimization of cost, GHG emissions</td>
<td>Relation between pump cost, GHG emissions, and system integrity</td>
<td>The methodology tested on a small network (residential span 11 km only)</td>
</tr>
<tr>
<td>(Kurek et al. 2013)</td>
<td>minimize pumping costs, water quality, and tanks sizing</td>
<td>Development of new tool to check the water quality and pumping operation</td>
<td>EPANET model (not real network)</td>
</tr>
<tr>
<td>(Zheng et al. 2014)</td>
<td>minimizing cost and maximization of the network resilience</td>
<td>An efficient hybrid approach for the design of (WDS) with multiple objectives</td>
<td>Proposed methodology verified on the New York water channels and Hanoi-network only</td>
</tr>
<tr>
<td>(Bi et al. 2015)</td>
<td>optimal pipe diameter and pressure head</td>
<td>Use of new heuristic algorithms approach of varying size WDS</td>
<td>Pumping power not considered in the proposed methodology</td>
</tr>
<tr>
<td>(Siew et al. 2016)</td>
<td>minimum node pressure, conservation of mass &amp; energy, pump scheduling, tank sizing</td>
<td>spatial and temporal variations in water quality investigated in addition to water age</td>
<td>Not real network</td>
</tr>
<tr>
<td>(Lence et al. 2017)</td>
<td>minimize pipe network cost and maximizing the number of reliability</td>
<td>proposed a fuzzy multi-objective programming for pipe design</td>
<td>Methodology applied to design pipe diameter (water-mains only)</td>
</tr>
<tr>
<td>References</td>
<td>No of tanks &amp; pumps</td>
<td>Location</td>
<td>Hydraulic model</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------</td>
<td>----------</td>
<td>----------------</td>
</tr>
<tr>
<td>(Lopez et al. 2005)</td>
<td>--</td>
<td>Van Zyl model</td>
<td>Parallel ACO + EPANET</td>
</tr>
<tr>
<td>(Ostfeld et al. 2006)</td>
<td>3, 8</td>
<td>Ostfeld &amp; Salomon’s (2004) network model</td>
<td>EPANET</td>
</tr>
<tr>
<td>(Bunn et al. 2007)</td>
<td>--</td>
<td>EBMUND/ Washington Haifa- A (Mount Camel), Israel</td>
<td>Aqueduct</td>
</tr>
<tr>
<td>(Salomon et al. 2007)</td>
<td>12, 30</td>
<td>T- China</td>
<td>Genetic simulation annealing (GSA)</td>
</tr>
<tr>
<td>(Gibbs et al. 2010)</td>
<td>--</td>
<td>Woronora, WDS Sydney, Australia</td>
<td>EPANET Model</td>
</tr>
<tr>
<td>(Shihu et al. 2010)</td>
<td>12, 30</td>
<td>Kenitra, Agadir City, (Morocco)</td>
<td>Genetic simulation annealing (GSA)</td>
</tr>
<tr>
<td>(Mouatasim et al. 2012)</td>
<td>5, 8</td>
<td>Ostfeld network model</td>
<td>EPANET Model</td>
</tr>
<tr>
<td>(Mala et al. 2014)</td>
<td>1, 8</td>
<td>Madeira, Portugal</td>
<td>EPANET Model</td>
</tr>
<tr>
<td>(Coelho et al. 2014)</td>
<td>2, 1</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

"--" No Data Available
Table 6: Multi-objective approach used for pumping energy cost optimization and GHG emissions in WDSs

<table>
<thead>
<tr>
<th>References</th>
<th>Study area and location</th>
<th>Multi-objective variables/ optimization methods</th>
<th>WDS layout</th>
<th>Energy, cost saving</th>
<th>Energy saved</th>
<th>GHG reduction</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Boulos et al. 2010)</td>
<td>hypothetical model, (later used in Europe’s 8 WDS)</td>
<td>Min. service pressure, energy, and GHG emissions</td>
<td>Four pumping stations</td>
<td>$4 million operating cost &amp; 38% energy saved</td>
<td>754 kW pump potential energy saved</td>
<td>3454 x 10^3 kg CO₂/year</td>
<td>Model is applicable for a small network, topography not considered, tradeoffs suggested between economic, environmental, and hydraulic reliability</td>
</tr>
<tr>
<td>(Wu et al. 2009, 2010 2013)</td>
<td>hypothetical model, Duan et al. (1990)</td>
<td>Min. Cost, (GHG), max. hydraulic reliability</td>
<td>One pump, one storage tank, 36 pipes and 16 demand nodes</td>
<td>$10 million saved</td>
<td>-</td>
<td>315 kt</td>
<td></td>
</tr>
<tr>
<td>(Roshani et al. 2012)</td>
<td>Amherstview Ontario</td>
<td>min cost, energy, and GHG</td>
<td>Two pumps, three tanks, one reservoir /15000 inhabitant</td>
<td>-</td>
<td>2% of total energy saved</td>
<td>10 kt / over 50 years</td>
<td>Small network</td>
</tr>
<tr>
<td>(Balinco et al. 2014)</td>
<td>South Australia the model derived from Wu et al. 2010</td>
<td>min cost, energy, and GHG</td>
<td>One tank &amp; 1 pump</td>
<td>$0.068/m^3 cost reduce</td>
<td>1.8 %</td>
<td>0.145 kg CO₂-eq/m^3</td>
<td>Small network</td>
</tr>
<tr>
<td>(Stokes et al. 2014)</td>
<td>hypothetical model (D town) derived from Salomon et al. 2012</td>
<td>min pumping operation, GHG time varying emissions factor</td>
<td>Seven storage tanks and 12 pumps in 5 pumping stations, 400 pipes, over 350 demand nodes</td>
<td>-</td>
<td>-</td>
<td>0.574 kg CO₂-e/kWh</td>
<td>EF (emission factor) depends upon various electricity generations methods</td>
</tr>
<tr>
<td>(Badruzzaman et al. 2015)</td>
<td>Eastern Municipal Water District (EMWD), California</td>
<td>Min. pumping operational &amp; GHG</td>
<td>Large WDS</td>
<td>22% cost reduction</td>
<td>6–15%</td>
<td>6% less GHG emissions</td>
<td>Offline software simulations and real network optimized values not agreed trade-offs between kWh and cost reduction</td>
</tr>
<tr>
<td>(Cherchi et al. 2015)</td>
<td>Water utility California</td>
<td>min pumping energy, cost, &amp; GHG</td>
<td>Three pumps, five tanks</td>
<td>5-20% cost reduction (6-15% energy reduction)</td>
<td>14000 kWh/week</td>
<td>0.2 metric ton-CO₂/week</td>
<td>the extra cost of renewable energy resources, a small network</td>
</tr>
<tr>
<td>(Ruben et al. 2017)</td>
<td>UK (Van Zyl model, 2004)</td>
<td>min pump electricity costs and GHG</td>
<td>Two tanks, three pumps</td>
<td>-</td>
<td>19%</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

“-” Data not available
Table 7: Characteristics of energy efficient control system used for water pumping system

<table>
<thead>
<tr>
<th>References</th>
<th>Objectives/variables</th>
<th>Energy saved</th>
<th>Contribution</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(UNICO Inc. 2010)</td>
<td>Pressure, flow and level control</td>
<td>20 to 50 %</td>
<td>developed synthesis intelligent pump (IP) controller to synchronize multiple drives</td>
<td>Volume measurement error can shut down the system</td>
</tr>
<tr>
<td>(ABB Motors 2012)</td>
<td>Pressure head, flow rate, and energy efficiency</td>
<td>10-50 % of total pumping energy</td>
<td>developed intelligent pump control software</td>
<td>Application in parallel pumps only</td>
</tr>
<tr>
<td>(Danfoss 2012)</td>
<td>Pump head, flow rate</td>
<td>30 to 50 % energy saved at a lower pump speed</td>
<td>Developed sensor-less controller for pump head and flow</td>
<td>Less malfunction but the high price</td>
</tr>
<tr>
<td>(Siemens 2015)</td>
<td>Speed, flow rate</td>
<td>controller reduce energy cost up to 20 %</td>
<td>developed ultrasonic controller for water supply pump scheduling</td>
<td>High maintenance cost</td>
</tr>
<tr>
<td>(Vogel GmbH (2015)</td>
<td>Pressure, speed</td>
<td>Up to 50 % energy saved to run variable speed pumps</td>
<td>Developed Hydrovar the sensor-less controller of a centrifugal pump</td>
<td>Up to 8 pumps can control at a time</td>
</tr>
<tr>
<td>(Armstrong 2017)</td>
<td>Power, pressure, flow rate</td>
<td>30-50 % energy saved at peak load</td>
<td>developed an intelligent variable speed sensorless pump</td>
<td>High price, used for small network</td>
</tr>
<tr>
<td>Reference</td>
<td>Location</td>
<td>Population</td>
<td>No. of scenarios</td>
<td>Estimated energy use kWh/m³</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>(Sahely et al. 2005)</td>
<td>Toronto Canada</td>
<td>2.6 million</td>
<td>0</td>
<td>0.60</td>
</tr>
<tr>
<td>(Lassaux et al. 2006)</td>
<td>Walloon region Belgium</td>
<td>3.5 million</td>
<td>5</td>
<td>--</td>
</tr>
<tr>
<td>(Friedrich et al. 2009)</td>
<td>Durban South Africa</td>
<td>3 million</td>
<td>4</td>
<td>0.10</td>
</tr>
<tr>
<td>(Muñoz et al. 2010)</td>
<td>Malaga Spain</td>
<td>0.5 million</td>
<td>2</td>
<td>0.50</td>
</tr>
<tr>
<td>(Herstein et al. 2011)</td>
<td>Any-town benchmark Model</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(Qi et al. 2012)</td>
<td>Manatee County U.S.A. Mid-Western U.S. water utility</td>
<td>0.3 million</td>
<td>20</td>
<td>--</td>
</tr>
<tr>
<td>(Amores et al. 2013)</td>
<td>Tarragona Spain</td>
<td>0.14 Million</td>
<td>3</td>
<td>0.48</td>
</tr>
<tr>
<td>(Venkatesh et al. 2014)</td>
<td>Oslo Norway</td>
<td>0.5 million</td>
<td>0</td>
<td>0.18</td>
</tr>
<tr>
<td>(Nault et al. 2015)</td>
<td>Southern Ontario</td>
<td>12 million</td>
<td>11</td>
<td>0.68</td>
</tr>
<tr>
<td>(Wakeel et al. 2016)</td>
<td>Lahore, Pakistan</td>
<td>12 million</td>
<td>-</td>
<td>0.62</td>
</tr>
<tr>
<td>(Sambito et al. 2017)</td>
<td>Palermo metropolitan Sicily, Italy</td>
<td>0.8 million</td>
<td>1</td>
<td>0.28</td>
</tr>
</tbody>
</table>

* TC = Temperature Change, Op = Operation, Cons = Construction, CED = Collective Energy Demand, "--" = No data available