The Water and Energy Nexus

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Abstract

Water has always been mankind's most precious resource - there are no substitutes. The struggle to control water resources has shaped human political and economic history. Population growth and economic development are driving a steadily increasing demand for new clean water supplies and it is well documented that lack of access to clean water has major health implications. Many see the water security as the key environmental issue of the 21st century. Water and energy issues are inextricably linked. Energy is needed to extract water from underground aquifers, transport water through canals and pipes, manage and treat wastewater for reuse, and desalinate brackish and sea water to provide new fresh water sources. Water is crucial for the energy production, for hydropower dams, for cooling of thermal power plants, and for fossil fuel production and processing.

Water and energy are the critical elements of sustainable economic development – without access to both of them economies cannot grow, jobs cannot be created, and poor people cannot move out of poverty. On a global basis, neither water nor energy are in short supply. What is in short supply is energy and water at a price that people can afford to buy. We have to find better ways to use the water wisely, in our homes, in agriculture (such as "smart" irrigation), and in industry. Using the water wisely includes producing the potable water and cleaning the wastewater using less energy. Pumping water, pressurizing water distribution systems, and pumping wastewater are major energy consumers. Aeration of activated sludge systems is another major energy consumer. A wastewater treatment plant can also serve as an energy producer. The interest in biogas is increasing and there is a large unused potential in maximizing the production of biogas. Using desalination for water supply is rapidly increasing and this requires huge amounts of energy. Control and automation in water and wastewater operations can contribute to improve the sustainability by smart monitoring systems, disturbance attenuation, using energy wisely and to maximize energy production.

Sustainable solutions require that we do not address singles issues in isolation, but have to adopt a systems approach with integrated solutions. The whole system has to be considered, including pure water resources, energy consumption, water usage, wastewater treatment, water reuse, receiving water and possible energy production. Still it must be remembered that technology offers only part of the solution. The attitude towards water consumption may be the crucial ingredient. Furthermore, new approaches to financing, managing and maintaining systems must be developed.

Keywords: energy, efficiency, water treatment, wastewater treatment, biogas, energy production, control, automation

1 Definition of the subject

Water and energy are inextricably linked. Water is needed to generate energy and energy is needed to extract, treat and distribute water and to clean the used and polluted water. This is the water-energy nexus and as a consequence both challenges must be addressed together. Energy, water and environmental sustainability are closely interrelated and are vital not only to the economy but to the health and welfare of all humans.

As a consequence of the close interrelationship between water and energy the design and operation of water and wastewater systems should take the energy aspect into consideration. Similarly, energy

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production can not be planned without taking water resources and water quality into consideration. Water availability is often undervalued and taken for granted. Population growth, climate change, urbanization and rising health and environmental standards increasingly call for an integrated approach. The design of our cities, suburbs, homes and appliances has enormous implication for water and energy consumption. As a result we cannot continue to utilize the critical resources water and energy in an inefficient and wasteful manner.

In this chapter we will focus on the following main issues:

- Section 2: How the interrelationships between water and energy look like;
- Section 3: Efficient design and operation of water and wastewater facilities;
- Section 4: Attention to the water related energy use at the end user;
- Section 5: Energy recovery from wastewater, such as biogas production;
- Section 6: The use of monitoring and control to make operations more efficient;
- Section 7: Water requirements for energy production

In the last two sections 8 and 9 we summarize some of the findings and look for some future directions to deal with the water and energy nexus.

2 Water and energy interdependencies

The interdependence between water and energy has been recognized during the last few years. Allan Hoffman wrote in 2004 [1] on the topic: "The energy security of the United States is closely linked to the state of its water resources. No longer can water resources be taken for granted if the U.S. is to achieve energy security in the years and decades ahead. At the same time, U.S. water security cannot be guaranteed without careful attention to related energy issues. The two issues are inextricably linked". In the USA the Energy-Water Nexus initiative was initiated in 2004 as an informal DOE National Laboratory initiative to develop a better understanding of the link between the nation's energy and water supplies. The laboratories conducted preliminary assessments that indicated that the interdependence between energy and water supplies were much broader and much deeper than initially thought [1].

The increasing scarcity of water has been given much attention on the World Water Forums (1997 and every 3 year), UN Millenium Summit (2000) and now we are in the middle of the UN Decade of Water (2005-2015). Special workshops and conferences have been arranged, such as [2], [3], [4] and an interesting overview is found in [5].

Increasingly there is a risk that water and energy interests are in conflict. Some examples can illustrate this:

- Between 1 and 18% of the electrical energy in urban areas is used to treat and transport water and wastewater. Furthermore, the energy related to water use – mostly heating the water in households and industries – requires about ten times more energy compared to the energy needed to deliver the clean and cold water and to treat the wastewater.
- To treat impaired water to drinking standards requires more energy. Most water treatment plants today are gravity draining through sand with some chlorine added. But as contaminants grow, old technology doesn't work. Either membrane or thermal water treatment is more energy intensive than traditional methods.
- Thermal power plants require huge amounts of cooling water. For example, around 39% of all freshwater withdrawals in the USA are used for thermoelectric energy production. This is roughly the same amount of water as for irrigation [6]. Most of the cooling water is returned but around 3% is actually consumed, mostly by evaporation. Water availability has become a contentious siting issue for thermoelectric power plants and must compete with demands from municipalities, agriculture and other industries.

- Climate change and increasing drought in many regions will decrease the flow in many rivers. Consequently the cooling water may become insufficient for the need of the thermal power plants along the river.
- Energy exploration and production requires a lot of water and consequently will generate a lot of wastewater. Pure water is injected down a hole for oil or gas production, fracturing the shale formation to release oil or gas. Then the water is brought back up with the oil or gas. The water is then severely contaminated. Today that water is injected thousands of meters down where it evaporates and is out of the water cycle.
- It is apparent that hydropower generation depends on water. A hydropower dam can be a serious environmental problem. The dam itself often serves as a gigantic sedimentation basin, and the solid material that earlier served as fertilizers downstream now are trapped in the dam. Obviously the water flow downstream is affected. This has implications for the agriculture, water fauna, for recreations and many other human activities. Increasing water shortage in combination with increased water use in many regions is now causing lack of water in the dams. With lower water levels the generation of electricity is decreasing.

It is critical to understand the key roles and responsibilities associated with the management, operation and use of the water and energy resources. This includes government agencies, private industry as well as individual users. The interdependencies between water and energy should force us to conduct planning and operation in such a way that both the water and energy flows are tracked. Such a systems analysis should recognize the inputs and outputs for each aspect of the system as well as the storage reservoirs for the entire system.

The supply of water

Considering the importance of the topic it is interesting to examine how much resources have been spent on water resources research. The situation in the US is interesting. Since 1973, the population of the United States has increased by 26 percent, the GDP and federal budget outlays have more than doubled, and federal funding for all research and development has almost doubled, while funding for water resources research has remained stagnant [7]. Still, the pressure on water resources increases with population and economic growth. There is an increase in the number of conflicts over water, so there are strong incentives to focus much more on the water and energy issues, both in many parts of the industrialized world and in the developing world.

The economy of water and energy behaves in a particular way [8]. When the supply is scarce there is a high price inelasticity of demand. A small reduction of supply leads to a huge increase in price. As a result the total value (price · quantity) rapidly increases as total quantity declines [9]. This is true for any resource that is essential and non-substitutable. As there is less water or energy available, their price quickly increases. This can create havoc in markets and stress the whole economic system. Diminished water supplies may lead to direct conflict and violence.

When energy and water supplies are abundant, their value is low. It may seem that we have an infinite supply and there is no need to worry. However, as we approach depletion, even small perturbations due to unforeseen climatic events, sharp increases in demand or technical malfunction result in disproportionate changes in their values and prices, if the market is allowed to work.

When energy supply of non-renewable fossil fuels is depleted we are looking for renewable sources. Similarly, we are over-utilizing fresh water resources in many places. This is compensated by increasing the energy use to import water from other basins (such as S. California, Table 1), desalinate salt water or reuse wastewater. Furthermore, non-renewable water is depleted by over-pumping from fossil aquifers. These practices are not sustainable and will leave our children with fewer options. We need to think much more in terms of increased efficiency and conservation.

3 Energy use in water and wastewater operations

Energy is needed to extract water from underground aquifers, transport water through canals and pipes, manage and treat wastewater for reuse, and desalinate brackish and sea water to provide new fresh water sources. To get the energy data is not always easy. Statistics for water abstraction, treatment and distributions are maintained by OECD and Eurostat and also by UN for different sectors. However, the corresponding energy consumption is usually not recorded in the water statistics, so it is not easy to recognize the interconnection.

Using the water wisely includes producing the potable water and cleaning the wastewater using less energy. Pumping water, treating the water to drinking quality, pressurizing water distribution systems, pumping and treating wastewater is a major energy consumer. In the USA and in the UK this amounts to about 3% of the nation's electrical energy use. In Sweden the corresponding number is 1%, while in Israel it is around 10%. This also means that water extraction and cleaning will have an impact on the greenhouse gas (GHG) emission. On a global basis the water/wastewater sector contributes with 1,5% of the CO_2 and about 5-7% of the GHG emissions. With increasing population and demand growth the GHG emissions will most likely exceed the 7% [9].

Some national water utility associations maintain statistics on energy consumption by the water sector. The power consumption follows typically a daily, weekly and sometimes seasonal use pattern. There is a potential for compensating some of the daily use pattern by pumping to water storage reservoirs during low load hours for the power plants and vice versa for the high load hours.

Drinking water production is increasingly crucial, in particular in dry countries. The use of desalination is growing at a significant rate in many industrialized countries, and this development further emphasizes the close coupling between water and energy. At the same time, billions of people in developing countries have not yet turned on the first electrical light. This means that the structure of electrical energy generation and distribution has to be carefully considered. There is a wide variation of the electrical energy needed to produce drinking water. The large differences reflect both the different efforts needed to obtain the clean water and the water consumption. Table 1 shows some examples to illustrate the energy requirements to produce clean water.

Table 1. Energy requirements to pump 1 m^3 to the water treatment in some different places (data from [10], [11])

Location	**kWh**
Sweden (average)	0,22
Sweden lowest	0.04
Sweden highest	0.64
N. California, USA	0,04
S. California, USA	2,3
Melbourne, Australia	0,09
Adelaide, Australia	1,9

S. California and Adelaide are dry places, and the water has to be pumped long distances. This is reflected in the very high energy costs for these places. The energy can be compared with the energy requirement to desalinate seawater, which is typically 4 kWh/m^3. If there were unlimited energy, we would never have a problem with obtaining water for use. For example, there are vast resources of saline water that could be desalinized to provide for all the imaginable demands for water if there is energy to run those operations and then pump water to wherever it is needed. That is certainly not the case.

Wastewater collection, treatment and discharge, sludge treatment and disposal require electrical power for pumping and aeration in biological treatment processes. Again, statistics for wastewater generation, collection and treatment as well as sludge generation and disposal are maintained by OECD and Eurostat and also by UN for different sectors. As for water supply, the corresponding energy consumption is seldom recorded in the water statistics. Some national water utility associations maintain statistics on energy consumption by the water sector.

Primary treatment of wastewater is sometimes called mechanical treatment. Pollutants are removed by sedimentation or filters and the solids are removed by scrapers. Biological nutrient removal (BNR) is a term used to describe plants that employ biological processes to remove organic matter (C) as well as nitrogen (N) and phosphorous (P). The activated sludge process was developed in the early 1900s with the purpose to remove components that consume oxygen. When the effect of eutrophication became known, the next important step involved the development of processes that could remove nitrogen and phosphorous.

The most important process for removing organic matter is biological oxidation, which involves microorganisms feeding on the carbon and the oxygen in the water. Some of the carbon is used for the growth of the microorganisms and the remainder is converted into carbon dioxide. In the microorganisms around half of the organic matter is used to increase the body mass and half is converted into carbon dioxide.

Nitrogen principally arrives at the plant as ammonium (60-80%). Most nitrogen removal plants will transform the ammonium into free nitrogen that will escape via the water surface. The removal of nitrogen is a slower process than the removal of organic carbon and takes place in two principal stages, nitrification and denitrification. In the first process ammonium is transformed into nitrate (an oxidation process) and in the second process the nitrate is reduced to nitrogen gas.

The concentration of dissolved oxygen governs carbon removal, nitrification as well as denitrification. In the carbon removal and nitrification the process rate will increase with the oxygen concentration. However, there is a limit to the process rate, and higher dissolved oxygen concentrations will not help the biology but only waste energy for the compressors that aerate the biological reactor. On the other hand, with too little oxygen the microorganisms (like humans!) will suffocate and the process rate will be significantly reduced. In the extreme case the organisms will die. The opposite applies to the denitrification: the higher level of dissolved oxygen the lower the rate.

To aerate the biological reactors is an energy consuming process. This means that the aerator has to be controlled so that it balances between the biological need for oxygen and the energy cost to supply the air. Table 2 gives some Australian figures to illustrate the variability.

Table 2. Energy requirement for wastewater treatment in Australia (data from [10] and from Sydney Water and Brisbane Water)

Type of operation	**kWh/m^3 (min, max)**	**kWh/m^3 average**
Primary	0.1 – 0.37	0.22
Biological C removal (incl. primary)	0.26 – 0.82	0.46
Advanced C, N and P removal	0.39 - 11	0.90

As a comparison the UK water industry uses 0,63 kWh to treat 1 m^3 of sewage and 0,59 kWh to treat 1 m^3 of water [12].

The two major energy consumers in wastewater treatment are pumping of the influent wastewater and aeration. The difference between the primary treatment and the biological and advanced treatment is mainly due to the aeration energy. Typically aeration in the biological treatment systems represent around 50% of the wastewater operating costs, while pumping represents around 60% of water treatment operating costs.

To relate the energy use to the volume of water only tells part of the truth. In order to get adequate key performance indicators it is important to relate the energy consumption both to the amount of organic components, nitrogen and phosphorus removed.

There is a significant difference between the energy requirements for different wastewater treatment plants. The differences are due to plant size, the type of load (for example industrial or mainly domestic) and the type of operation. For example, in Sweden the energy requirement for wastewater operations varies from 1.5 to 40 kWh per kg BOD (organic carbon removal), with a median value of 4.5 kWh [11].

In some countries there is already a demand to decrease the energy requirement for water and wastewater operations. In California a 20% increase in energy efficiency will be required according to the California Water Plan Update 2009. In China the central government will require at least a 20% decrease in energy use [13] and in Sweden a new energy savings program is being implemented where the goal is to save at least 20-30% in electrical energy requirement for wastewater treatment operations [11]. In Germany the Ruhrverband has managed an ambitious energy savings program [14].

According to [2] it is quite feasible to obtain an energy consumption reduction by 20% by optimisation and innovation. The existing systems in the water and wastewater industry haven't reached the limits of improvement of its energy efficiency yet [15], [16]. It was also stated at the workshop [2] that a further reduction of the energy consumption with another 80% should be possible, but this requires a paradigm shift. The current water infrastructures have been designed and constructed on the basis of views, requirements, conditions and technologies of decades ago. It is recognised that in the present systems wastewater treatment, water treatment and distribution are very energy intensive. New concepts could include topics like alternative sanitation approaches (vacuum system, separation at the source), from waste towards resource (P and N recovery; wastewater as nutrient for algal based biofuel), microbial fuels cells, tailored water quality and use of alternative resources etc. The water and wastewater sector could benefit for technology developments and breakthrough in related areas like i.e. energy production, sensor development, nanotechnology etc. Many research efforts have already been done in this direction [17].

Some of the important areas where energy efficiency needs to be addressed are:

- Water and wastewater pumping efficiency, including primary pumping, recirculations and sludge pumping;
- Motor controls, including soft start;
- Aeration in biological treatment systems;
- Mixing;
- Water losses;
- Demand side management – consumer behaviour;
- Operation of anaerobic digesters.

Every energy efficiency improvement has to be tested from two angles: (1) How is the process affected, and (2) what is the cost of the efficiency improvement. Every wastewater treatment operator is responsible for the effluent water quality. Therefore the regulatory requirements are always the primary goal and the energy efficiency becomes secondary. At the same time it has been shown that sometimes a better efficiency will also create a better process performance.

There are two principal possibilities for better process efficiency, retrofitting the equipment and using control and automation. In the latter case one also has to consider the investment in instrumentation, actuators (such as controllable pumps and compressors) and computer control systems.

Here we will give a couple of example of efficiency improvements by retrofitting or control. By designing pumps for adequate flows, operating at dynamically changing pressures and using variable speed pumping there is a great potential for energy savings [18]. It is well-known that variable speed operation will save a lot of energy. Figure 1 illustrates the fact that the power requirement for pumping is proportional to n^3, where n is the speed of the pump. At the same time the flow rate is proportional to n. In other words, as the speed of the pump is halved the flow rate will be halved while the power requirement decreases to 1/8. This is the very basic motivation to use variable speed drives in order to save energy.

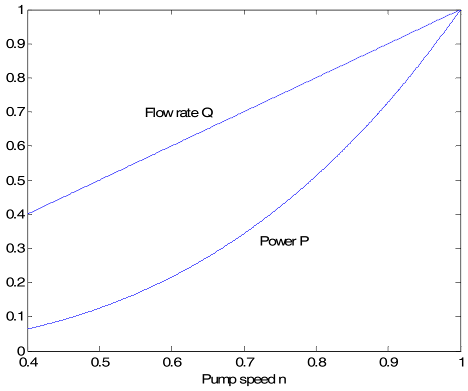

Figure 1. The relationship between the flow rate Q and the pump speed (n) (the upper curve) and the power P and the speed (the lower curve) according to the affinity laws.

It is not sufficient, however, to introduce variable speed pumping to save energy. The pump has to be designed so that its efficiency is at a maximum at the most common flow rate. This is a fact that is often overlooked in pumping of both water and wastewater systems.

Aeration of activated sludge systems is another major energy consumer. By automatic control of dissolved oxygen adjusted for variable wastewater loading more energy savings are possible, and as a bonus the biological activity is favoured. There is a wealth of literature of dissolved oxygen control and a state-of-the art is given in [19], while [20], [21] and [22] give further experiences and evidence. In another chapter of this book [23] more details will be explained.

Often the mixing of wastewater consumes too much energy. According to German experiences 2-3 W/m^3 is sufficient [14].

Energy savings can be obtained both by selecting the adequate equipment and by feedback control. Efficient pumping requires not only the proper pumps but also a control system that can adapt the pumping to the process needs. Likewise, energy efficient aeration requires not only sensors for dissolved oxygen and air flow rate but also controllable compressors and adequate air valves.

Water saving is directly related to energy saving, also in water industry operations. Leakage reduction, metering, recycling and demand reduction all contribute to less waste of water.

4 Energy on the demand side

A lot of efforts are today spent on the supply side instead of on the conservation and efficiency side. For example, in Nevada, USA, the Southern Nevada Water Authority states [8]: “One of the main objectives of the Authority is to obtain additional water from Colorado River to support urban growth of its member agencies.” In general, hardly any water utility or water company has direct responsibility to reduce demand. At the same time, problems with energy and water supply are looming.

A lot of energy is used for bottled water. Only in the USA the bottled water industry is a $15 billion industry and this industry consumes a lot of energy to manufacture, package and transport bottled water over huge distances [8]. The average American in 1976 drank 6 liters of bottled water a year, according to Beverage Marketing Corp. In 2009 the consumption was 108 liters, more than 2 liters per week. According to [24] "we are moving one billion bottles of water around a week in ships, trains, and trucks in the United States alone. That's a weekly convoy equivalent to 37,800 18-wheelers delivering water." Actually 24% of the bottled water the Americans buy is tap water repackaged by Coke and Pepsi. Every year 50 billion water bottles are used in the USA – 167 for each person - and 38 billion of them are pitched into landfills in the USA. This is more than $1 billion worth of plastic that represents a lot of wasted energy. Actually only 23% of the recyclable polyethylene terephthalate (PET) plastic bottles are actually recycled.

There is an interesting and strange attitude towards water. In a country like Sweden the tap water quality is excellent, and from a quality point of view bottled water will never be needed to replace the tap water. Still the Swedes consume around 30 liters of bottled water per person and year. They pay 3-4 times the price for gasoline for the water, which is around 3000 times the price for the tap water. In a recent examination (2009) of bottled water only 2 out of 15 brands of bottled would be accepted as tap water according to the drinking quality standards.

Water usage has an energy cost. Both energy use and water use have to be sustainable. The use of suitable energy sources is discussed elsewhere and is outside the scope of this chapter. However, also the consumption of water has to be sustainable. Recent droughts have put the focus on the water consumption in some countries. It is apparent that the water consumption is quite different in different countries. Looking at individual cities (100 cities compared) the specific water consumption varies globally from 0.34 to 650 litres/capita/day [25], while the total charge for drinking water varies from $0,015/m^3 to $3.13/m^3. Some national comparisons are given in Table 3.

Table 3. Water consumption in some countries (sources [8], [26])

Country	**Water use Liters/cap/day**			**Water Poverty Index (scale 0-100)**
	Domestic	Agriculture	Industry	
USA	600	1900	2100	65
Australia	500	2600	340	62
Canada	800	480	2800	78
China	85	910	345	51
Germany	190	310	1060	65
The Netherlands	80	460	820	69
India	140	1500	95	53

The Water Poverty Index has been developed in [27]. Canada, Norway and Iceland are the countries with the highest index. No country has higher than 78. The index gives an assessment of the national water management and includes resources (water available), access to water supply and sanitation, economic standard, water use and water environment.

It is true that the natural conditions are quite different. Still these figures often reflect the habits and sometimes misuse of water. Naturally the price of water has a role to play here (see Section 2). In general, the price paid by the consumer has a direct influence on the amount that is used. In the USA the average household spends 0,006% of the income on water. The corresponding numbers for UK are 0,013%, for Pakistan 1,1% and for Tanzania 5,7% [26]. It is most often true that the poor people pay more. While the average USA household pays around $0,5 per m^3, and a German pays $1.9 poor people often depend on informal vendors. A typical water price in Dhaka, Bangladesh is $0.4 per m^3, in Phnom Penh, Cambodia $1.6 and in Manila Philippines $4.7 per m^3 [26].

Curbing demand is cheaper, faster, and ultimately more beneficial to individuals than increasing supply. Conservation of energy saves both energy and water. Optimal water use saves both water and energy.

It should be realized that more than 90% of the water related energy use is spend in the home. This is true for many industrialized countries. This fact is easy to realize just from a simple theoretical calculation. Usually only a fraction of a kWh is needed to produce 1 m^3 of drinking water. To heat this water from 15°C to 60°C requires 52 kWh, with no losses taken into consideration. Now, imagine how much warm water than can be saved by using the showers, washing machines, dishwashers etc. in a more economic way. Earlier it was stated that some 20-30% of the energy consumption for water and wastewater operations should be required. This saving should be profitable under most circumstances. Still, the same greenhouse gas emission savings could be achieved by only some 2-3% savings of warm water. Most water companies do not wish to take the responsibility for the domestic use of the water. Still, they usually have a good contact with the customers and should be able to easily influence the greenhouse gas emissions.

5 Energy recovery from wastewater

Energy recovery from sludge treatment is quite common and the biogas may be used for power generation, fuel for transport or heating. In some cases, installation of heat pumps in wastewater treatment plant effluents has provided energy in terms of heat recovery. The power consumption in wastewater treatment and transportation follows typically a daily, weekly and sometimes seasonal use pattern. Stormwater handling occasionally adds to the energy requirement. There is a potential for compensating some of the daily use pattern by conducting certain treatment processes during low load hours for the power plants and vice versa for the high load hours.

A wastewater treatment plant is not only an “end-of-pipe” solution to clean wastewater. It can also serve as an energy producer. The interest in biogas is increasing and there is a large unused potential in maximizing the production of biogas, used for both heating and as a replacement of gasoline in transportation, [28], [29], [30], [31]. Recent data show that anaerobic digestion uses only some 20% of the energy content of the sewage. By-products from sewage treatment in combination with organic solid waste can provide a valuable source of energy if managed and utilized effectively. About 1/3 of the chemical energy in the biogas can be transformed into mechanical energy The rest of the energy becomes heat, but this can of course be recycled and used for heating. In order to use the biogas for engine fuel the gas has to be further upgraded by removing carbon dioxide and hydrogen sulphide.

The biogas is produced in an anaerobic process where microorganisms break down the organic content of the sludge in the absence of oxygen. The process produces a methane and carbon dioxide rich biogas. Furthermore, the nutrient rich digestate can be used as fertiliser. The first part of the process is a so called bacterial hydrolysis where organic polymers in the input material break down to become available as food for other organisms. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia and organis acids. These organic acids are then converted into acetic acid by Acetogenic bacteria, and additional ammonia, hydrogen and carbon dioxide are generated. Finally, the products are converted to methane and carbon dioxide by the Methanogenic bacteria.

There are several factors that can influence the energy balance in the sludge handling in a wastewater treatment plant:

- *Primary sedimentation*: it may be possible to separate more sludge in the primary sedimentation. As a result less organic carbon will be brought into the biological treatment step, so less aeration energy will be needed. In this choice the organic carbon is chosen to produce biogas. However, organic carbon is also needed in the nitrogen removal process and insufficient carbon may limit the nitrogen removal capability.
- *Sludge thickening:* One way to increase the biogas production is to improve the thickening of sludge before the anaerobic digester. With a more efficient removal of water from the sludge the sludge volume will decrease. Consequently the retention time of the digester can be increased. Also, less energy will be needed to heat the sludge before the digester.

- *Sludge heating*: the heat content of digested sludge can be used to heat the incoming sludge.

In cold countries the heat content of the effluent water can provide significant heating not only to the plant facilities but also to city buildings via district heating systems [32]. In fact most wastewater treatment plants can be net producers of energy.

There are other optimization aspects to consider. From an energy perspective it looks straightforward to maximize the biogas production. However, from the digester there will be reject water that has to be recycled to the wastewater treatment process. This water normally contains high concentrations of ammonium nitrogen. Therefore the water that is recycled from the digester will significantly increase the load to the wastewater treatment plant, and thus to the energy requirement to operate the nitrification. This demonstrates that an energy balance has to be calculated in an integrated way and must consider the complete plant.

6 Monitoring and control for better efficiency

Monitoring

To track the process operational state via the instrumentation is called *monitoring*. For the clean water supply on-line monitoring will be required throughout the system including at the tap. The availability of low cost instrumentation will encourage better leakage detection [33], [34] and water quality monitoring [19]. In wastewater treatment systems the use of instrumentation, control and automation has proven to significantly reduce the costs for operation and detection and early warning systems are key components in a sustainable water system. The development of reliable, affordable and robust online instrumentation systems has been significant. Computing power no longer is a constraint, which means that the combination of measurements and model prediction can serve successfully in many systems.

Leakage detection in water distribution systems is becoming increasingly important as energy prices are raised. Leakages can appear as sudden bursts or they can appear as losses that will only gradually grow in size. Today there are powerful automatic methods both to detect that a leakage or burst appears, but also to locate the position with great accuracy. This can be obtained both in single pipe systems and in pipe networks. The idea of early warning and problem detection is fundamental. The losses caused by late detection can be significant. Leakages cause not only losses to the various damages of the leaking water. The extra energy to pump leaking water is significant, and it is not unusual to find 30-40% water losses in water distribution system. This power loss is intolerable, but still surprisingly accepted.

Similarly, early warning systems composed by arrays of sensors in drinking water intakes can prevent severe quality disturbances into the system.

Automatic monitoring is also crucial in wastewater treatment operation. Of course it should be related to the influent flow rate, concentration and composition. Furthermore, monitoring equipment operation makes it possible to early detect malfunctions, so that major process faults can be avoided. Several examples of this are given in [19], [35], [36], [37].

Control

The fundamental principle of control is feedback. The process (for example, an aerator, a chemical dosage system, or an anaerobic reactor) is all the time subject to disturbances. The current state of the process has to be measured by some sensor and this is the basis for a decision. In order to make a decision the goal or purpose of has to be expressed. Having made the decision it has to be implemented via an actuator, which is typically a motor, a pump, a valve or a compressor. In other words: *control is about how to operate the plant or process towards a defined goal, despite disturbances* [38].

Traditional wastewater treatment plant control is still unit process oriented to a great extent. Some examples of state-of-the-art control that will influence the energy efficiency are [19], [39]:

- Aeration control has the purpose to supply the microorganisms with adequate dissolved oxygen while saving maximum energy. Dissolved oxygen control will save a lot of electrical energy compared to no control at all. A time varying setpoint of the dissolved oxygen concentration will further reduce the energy consumption.
- In a sequential batch reactor the length of the different phases should be controlled. During the ammonia nitrogen oxidation time the aeration is controlled until all the ammonia nitrogen has been consumed;
- The control of anaerobic processes aims at regulating the biogas flow, at stabilizing the process and at maximizing its productivity. Still current state-of-the-art focuses on the unit process operation;
- In Section 5 some examples of integrated control for biogas production were presented.

7 Water use and impacts on the aquatic environment from energy production

The demand for water is growing. The world water demand has more than tripled over the past half century. In the year 2000 the global water use was estimated to be about 30% of the world's total accessible fresh water supply. That fraction may reach 70% by 2025 [1].

This means that there will be more competition for the water needed for energy production. As a consequence more water intensive energy producers will be forced to look for more efficient alternatives. A key indicator may be "energy return on water invested" [8], [40].

Hydropower is often considered as "green" energy in the sense that the electric power production does not generate any emissions of greenhouse gases. Hydropower now generates about 19% of the world´s electrical power. However, there are many signs of serious ecological impacts of hydropower generation. Dams do not only influence downstream transport of sediments which has consequences for agriculture; they also serve as giant sedimentation basins. Fertilizers from the river no longer reach downstream agriculture. The sediments are instead collected on the bottom of the basin. Eutrophication in dams is another serious problem and evaporation from water dams in warm countries has not been sufficiently addressed as a great threat to freshwater availability. Dams can also act as physical barriers, restricting migration of aquatic wildlife.

On a global basis only about one third of available hydropower potential has been used. However, the environmental and social costs for large dams will probably prevent much further development of large hydropower systems. Still there is a potential for small hydropower plants – less than 10 MW – that could be adequate for remote rural areas. The reservoirs needed for large hydropower plants globally cover a surface area of around 500 000 km^2 – roughly the size of Spain. With a lot of hydropower in warm countries there is a huge loss of water due to evaporation. The social cost is also significant. Around 80 million people have been forced to move due to dam constructions.

Thermal power plant operations – both coal fired and nuclear – require large amounts of cooling water. For example, in the USA almost 40% of the withdrawn freshwater is used for cooling in thermoelectric plants; however, only about 3% is actually consumed, mostly by evaporation. Heating of the water and the risk of radioactive contamination present great environmental challenges. Addition of chemicals, for example inhibitors, anti-scaling agents and biocides in cooling towers may represent high environmental loads of hazardous substances. Although these are at relatively low concentrations, accumulation of chemicals can be harmful in the long term. A wide variety of processes are already employed in power plants to recover, recycle, and reuse water. An overview of these technologies is found in [41].

Climate change will add to the risks of conflict between water and energy. The efficiency of the cooling process depends on the temperature difference between the cooling water and the temperature related to the plant. Consequently there are strict requirements on the temperature of water that is used. With a higher cooling water temperature more water is needed to provide the same cooling effect. Most plants have regulations or other constraints that limit their ability to adjust their withdrawal rates. In the short run this means that they will get less cooling, a corresponding decrease in turbine backpressure, less efficient generation, and less electric energy for the same amount of raw energy input. Also, many nuclear plants have safety limits on intake temperature that could trigger complete shutdowns more frequently in altered climate scenarios. In addition, environmental concerns usually impose limitations on the temperature of water discharged back into the streams and reservoirs.

Water and energy industries are competing for the same resource. For instance, availability of cooling water is a key issue for many power plants. If a river's flow is reduced, as they can do seasonally, power plants may find there isn't enough water available for cooling. This issue will only become more critical with climate change. It is quite apparent that the water quantity and quality aspects are not always placed sufficiently high on the agenda of many power companies. It will be increasingly important to establish networks of water and energy professionals to deal with the close relationship between water and energy.

It is obvious that energy savings in households and in industry will have a large impact on the need for electrical energy and consequently on water consumption and ecology. Technology development, for example, using more efficient pumps, refrigerators, air conditioners and heating systems and power electronic motor control will offer a most significant impact on the total electrical energy use.

As an ironic consequence of technological development in developing countries, low cost asynchronous motors and pumps have increased the water extraction for agriculture. One reason for the non-sustainable groundwater pumping is that the surface water is too contaminated. In some cases this has had catastrophic consequences for groundwater levels and salinity of the soil. More efficient use of water for agriculture is therefore of paramount interest. This requires education, better equipment, probably economic support and also some new legislation.

The "environmental friendly" zeal for ethanol has not considered the extensive irrigation required for the grain that supply ethanol. The situation in Midwestern USA can illustrate the problem. If irrigation is used, at least 1 m^3 of water is needed for every 10 km travelled by an ethanol-powered vehicle [42]. According to [42], in case of ethanol fuelled vehicles, there is a need to move from our old way of thinking — gasoline used per km – to water used per km. This water is often extracted from aquifers in a non-sustainable way. Fossil water is used and will not be replaced for generations.

It should also be noted that various portions of the ethanol production cycle have different water requirements. For example, in biofuel production irrigation requires orders of magnitude more water than ethanol biorefineries, as shown in Table 4. However the intensity of water consumption can be much higher for refineries, where thousands of cubic meters of water are to be withdrawn on the spot, significantly changing local hydrology and requiring additional infrastructure to provide that water.

Table 4. Estimated use of water for various technologies of biofuel production (from [8]).

	Irrigation use l water/ l ethanol	Refinery use
Oil		0.5 – 1 l water/l gasoline
Corn	0-1900 l water	2 – 5 l water/l ethanol
Cellulose (Sorghum) sugar	0 – 400 l water	6 l water/l ethanol

According to estimates from U. S. Department of Energy (DOE), more than 4 liters of water are needed for every liter of transportation fuel produced, threatening the limited water supplies (DOE Report 2006:80). China announced that it needs to curb coal-to-liquid production, because of concerns over pollution and the volumes of water consumed. Nevertheless more recently it was announced that the facility "will start operating later this year and is expected to convert 3.5 million tons of coal per year into one million tons of oil products such as diesel for cars." [8]. They will use groundwater and recycled water from coal mines to supply the 8 million tonnes it will need each year. In some parts of China, 30 years ago the water table was 5 meters below the ground. Today it is 35-40 meters below the ground because the groundwater is used in an unsustainable way.

8 Conclusions

Water and energy are the two most fundamental ingredients of modern civilization. Without water people will die. Without energy we cannot produce food or run our homes or industries. Considering the close relationship between water and energy it is obvious that the challenges have to be treated in an integrated manner and single issues cannot be treated in isolation. An integrated approach means that the whole system has to be considered, including pure water resources, energy consumption, water usage, wastewater treatment, water reuse, receiving water and possible energy production. Integrated systems can only be considered by cooperation between several specialists. The interdisciplinary view has to be recognized, which also means that we have to exercise much more communication between engineers and scientists of different disciplines, but also between technology people and professionals in social sciences, behaviour sciences, economy and political decisions.

Saving energy and water is not just a technical challenge. Maybe the most important factor is our consumer attitudes and behaviour. This includes how we use hot and cold water for showers, dishwashers and washing machines. What kind of machinery is used? How do we consume water for gardening etc.? As an example, the long drought in Queensland, Australia has forced the authorities in Brisbane to enforce a decreasing consumption. In 2005 the consumption was 300 L/day/person and in 2007 this had decreased to 130 [43]. This included restrictions for external water use and recommendations for internal water consumption.

As the world population grows the demands for both water and energy increases faster than ever. It looks as if the world has become aware of the era of peak oil, seeing the fluctuations of the oil price. It seems that we are approaching an era of peak water – there will be lack of cheap water. The situation should already be considered a crisis, but the public in many developed countries has not grasped the urgency. Water is ultimately more important than oil, because it is more immediately crucial for life. We have government departments of energy. As Webber [42] points out we should have a Department of Water that would ensure the effective use of water. Water is certainly a human right, but it should not be free or cheap. If we think that water is important, we should put a realistic price on it. The attitude towards water consumption may be the crucial ingredient. Furthermore, new approaches to financing, managing and maintaining systems must be developed, as well as approaches to involve local communities.

The energy and water nexus has to be recognized by decision makers, researchers and engineers as a vital one. It will not only determine the way to extract, treat and distribute water and collect and treat wastewater. The role of water has to be fully recognized in the production of energy, both for electricity and for transportation. For individuals there are many ways to influence both the water and energy consumption in their daily lives, for example at home and when making transport choices. Creating the right pricing, policy and regulatory environment is critical to encouraging behavioural changes, and ensuring a sustainable use of water and energy.

Conservation of energy saves both energy and water. Optimal water use saves both water and energy.

Future issues

In the future water supplies and treatment will probably become more energy intensive. Readily accessible freshwater supplies are limited or have been fully allocated in some areas. The new alternative water resources considered are sea water, brackish water, produced water or impaired water. This means increased energy consumption for pumping at deeper depths and longer distances. New technologies to access and treat non-traditional water resources will require increased energy consumption per m^3 of water.

Many new technologies offer interesting solutions. Wave energy offers sustainable solutions for energy generation, and the combination of desalination plants and wave energy generation is likely to be a very interesting area for research and development for water professionals in cooperation with power systems researchers. Microbial fuel cells (MFC) offer another interesting combination of water and energy issues. MFCs present an interesting energy challenge and also offer sustainable treatment of biological substances as a by-product [43].

Heat production from groundwater or effluent water in treatment plants is technologically possible, and application rates should increase along with investment in relevant infrastructure, for example district heating systems could be applied at large scales.

Regulatory aspects of balancing the competing interests of water and energy needs by several sectors and industries is a multidisciplinary task. There is an emerging need to create professional platforms where such issues can be discussed and further developed on “neutral ground”. A focus should be on the development of concepts and motivating incentives rather than case specific matters. For example, water pricing represents an issue not only affecting water and wastewater utilities but also energy and agricultural sectors. It is obvious that new incentives and attitudes have to be developed in order to save water and save energy.

There is an urgent need for a paradigm shift from promoting growth to sustainability. Sustainable growth is impossible on a finite planet; we can only talk about sustainable development. We have created a global system that is closely coupled and crises in one location send waves of disruption throughout the system. The fact that we live in a globalized system creates new opportunities, but also increases our risks, since there may be no place to go in case of a collapse. It will be unlikely that one developed country or region will be able to maintain its high quality of life if the rest of the world will be in substantial crisis. We have become very interdependent worldwide

Glossary

Anaerobic – conditions in a biological treatments system characterized by the absence of oxygen in any of its forms

Anoxic – no oxygen present - nitrate instead of oxygen is used by the organisms

Aquifer – a natural underground layer that contains water

BOD – biochemical oxygen demand, a measure of the organic carbon content in the wastewater

Brackish water – water that is neither fresh nor salt

Denitrification – the conversion of nitrate-nitrogen to gaseous nitrogen through anoxic cell growth

Desalination – the changing of salt or brackish water into fresh water

Eutrophication – a significant increase in the concentration of chemical nutrients in an ecosystem

Evaporation – he process of liquid water becoming water vapour

Fresh water – water that contains only small amounts of dissolved solids

Groundwater – water that is pumped from aquifers

Nitrification – the conversion of ammonia-nitrogen to nitrite and nitrate-nitrogen through cell growth

Renewable resources – total resources offered by the average annual natural inflow and runoff that feed a catchment area or aquifer; natural resources that, after exploitation, can return to their previous stock levels by the natural processes of growth or replenishment

Salt water – water that contains significant amounts of dissolved solids

Surface water – water pumped from sources open to the atmosphere, such as rivers, lakes and reservoirs

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