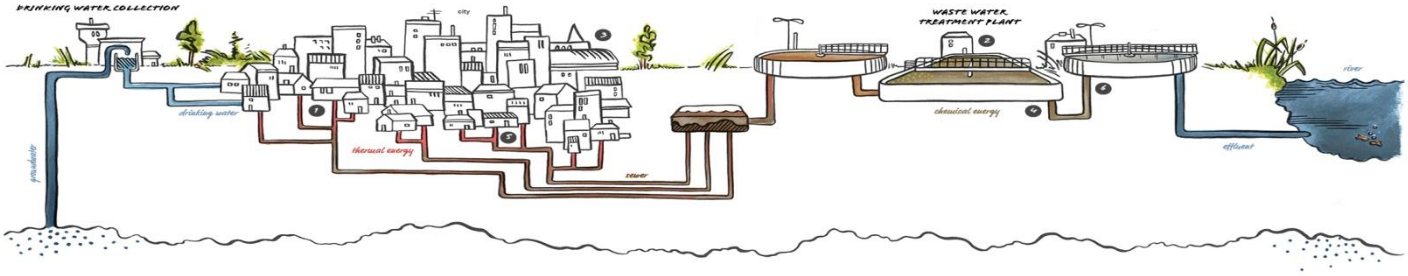

INNERS literature review:

An overview of energy used within the urban water cycle

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Executive Summary

The aim of this document is to give an overview of the amount of energy used in the supply, consumption and disposal of 1 m^3 of water as it travels through the urban water cycle. Supporting information has been drawn from a broad range of academic, water-industry, national government and EU literature, to enable a representative outline of water related energy consumption to be presented. Contrasting systems of reporting and governance at both the institutional and corporate levels, made finding common energy consumption values for each stage of the urban water cycle problematic. This was further compounded by geographic, climatic, topographical, hydrological, process and legislative differences that exist across the countries where existing data was available. Nevertheless by drawing on a range of examples from across selected OECD nations and examining a number of case studies, it has been possible to piece together the relationship between energy and water within the urban water cycle.

The review showed that in the case of drinking water provision the amount of energy used in the abstraction of groundwater is significantly greater than that used for surface water, which is often transported by gravity. Conversely the purification of surface water was found to be a much more energy intensive process than the purification of ground water. In all of the cases examined the greatest amount of energy consumed during freshwater abstraction, treatment and supply was expended on pumping. On average this activity accounted for around 60% of the energy used.

A key component of the literature review was to identify the amount of energy used in heating 1 m^3 of domestic hot water. This was deemed to be all hot water outside of the central heating loop. A study conducted by the Energy Savings Trust on behalf of the British Government reported the daily consumption of domestic hot water per household (litres) plus the temperature difference between the cold water entering the system and hot water leaving it, as the key variables required to establish values for energy consumption. By using the figures provided in this study a value of approximately 42 kWh/m^3 was calculated.

The information pertaining to the amount of energy used within the treatment and disposal of wastewater identified that a significantly lower proportion is used in pumping than is used in the abstraction and supply of drinking water. It also showed that relating energy use to the volume of wastewater being treated only provides part of the picture and that it is important to consider the type of treatment being supplied.

At the end of each section of this report energy values (kWh/m^3) are given for the stage of the urban water cycles being discussed. These are then brought together within the Discussion and Conclusions section in order that the key elements of each stage can be compared.

Contents

1 AN INTRODUCTION TO ENERGY USAGE WITHIN THE URBAN WATER CYCLE

The world's population is currently growing by approximately 80 million people a year and by 2050 is expected to reach 9 billion, 70% of which will be living in urban environments[1]. At the time of writing (2013) around half of all urban dwellers live in cities that have between 100,000 and 500,000 inhabitants and less than 10% live in megacities, i.e. those with populations exceeding 10 million people (World Health Organisation and UN Habitat Definition). This figure is expected to have changed markedly by 2025 as seven new megacities emerge taking the global total to twenty seven. The majority of these will be located in developing countries[2]. The resource implications of such growth on both the natural and urban water cycles are considerable, especially when we consider that the population rise alone is placing an increased freshwater demand of around 64 billion m^3 per year[3], on what is already a stressed and finite resource.

Within the context of this document the urban water cycle is deemed to comprise the following five stages: abstraction, treatment and supply; use by the consumer; the transportation of wastewater; and the treatment of wastewater prior to its eventual discharge into a water course. Urban and natural water cycles are differentiated by the fact that water is extracted from the natural water cycle to support anthropocentric activity.

Energy is also a resource that is vital to the maintenance of urban environments and the economic activities that underpin them and its supply is inextricably linked to water consumption. Projections to 2035 show no slowdown in growth of energy demand which is expected to rise by 53% to 770 quadrillion Btus (British Thermal Units)[4,5]. Table 1.1 contains a sample of the world primary energy consumption data and future projections in Quadrillion Btus (2008 -2035) published by the US Energy Information Association[6].

Table 1.1: World primary energy consumption[6]

	2010	**2025**	**2035**	**% Growth (2008 - 2035)**
Europe	79.6	89.7	93.8	0.5
USA	97.8	108.9	114.2	0.5
China	104.6	160.9	191.4	3.0
India	28.8	38.9	49.2	3.2

The International Energy Agency[5] has identified that the soaring dependence on coal-fired electricity production, will represent by far the largest strain on future water resources. Indeed if the trends hold steady on the number of coal-fired power stations coming on-line and the cooling technologies being employed, global water consumption for coal electricity alone would jump 84%, from 38 to 70 billion m^3 annually by 2035. Coal-fired power plants would then be responsible for more than half of all water consumed within energy production[5].

Over the period 2008 - 2035 global residential energy use is forecast to grow at an average rate of 1.1% per annum with the highest rate of increase occurring within the non-OECD nations, i.e. the 'newly emerging economies'. Energy consumption in non-OECD nations is expected to grow annually at around 1.9%, whereas in the OECD countries the anticipated increase is predicted to be much lower at 0.3%.

Given these energy and water demand projections, it is timely that the link between water and energy is now finding prominence within the climate change, carbon-reduction and water scarcity agendas. This resource relationship is generally referred to as the 'water-energy nexus' and has strong ties with the concept of 'urban metabolism', which has been used for the last 45 years to analyse urban flows of water, energy and materials[7]. However, despite significant efforts being made to optimize the urban water cycle in terms of cost and emissions, less attention has been paid to the system's total energy balance.

Within the UK water industry, energy use typically represents 28% of total operating costs and is reported to be the 2nd highest expense after labour[8]. During the abstraction, treatment and supply of clean drinking water, pumping alone equates to almost 60% of total energy used during this stage of the urban water cycle. The amount of energy used by pumping whilst abstracting water depends on whether it is being taken from a surface water or groundwater source. Cohen et al (2004)[9] have estimated that each 1 m^3 of groundwater pumped from a depth of 35 meters uses 0.14 kWh/M^3 of energy and that the same volume drawn from 120 meters requires 0.53 kWh[8]. Once water has been abstracted, it then needs transporting and figures reported in Scientific America (2008)[10] estimate that pumping water horizontally over 350 km requires 3.6 kWh/m^3. These figures are indicative and vary from one location to another depending on the distance and terrain over which the water is transported; the asset condition; and the pipe friction.

Within the wastewater treatment process only around 20% of the energy consumed is for pumping[11,] which is significantly less than the 60% used in supplying drinking water. The most energy intensive aspect of this stage of the urban water cycle is activated sludge aeration, which on average uses >55% of power. However, vast differences tend to exist between the energy requirements of one wastewater treatment plant and another. These are due to the broad range of geographic, economic, legislative, social and climatic variables that exist between them. For example, plant size and plant operations are contingent on the volume and type of hydraulic load received and this can fluctuate wildly from the operating norm as storm water enters the system. Consent limits for the discharge of effluent into receiving waters also influence the amount of energy used within the treatment processes. In cases where the receiving waters are particularly sensitive to the quality of waste being discharged in terms of its Chemical and Biological Oxygen Demand (COD/BOD), different treatment processes will be required than in less sensitive water courses. In such cases, the addition of nitrification to the activated sludge aeration process may be necessary; thereby increasing the amount of power used in this already energy intensive process to approximately 70% of net energy consumption[11].

In 2008, it was reported[8] that some Water Companies in the UK experienced increases in electricity consumption of over 60% since privatisation in 1989, due to advanced treatment processes and increased connection rates. This increase may also have been compounded by the fact that the UK's population grew from 56.98 million in 1989 to 61.35 million in 2008[12], assuming that this increase in population also created an increased demand for water. Conservative estimates in energy consumption predict a further rise of between 60 – 100% over the next 15 years in order to meet EU Directives on water quality. Specifically these are: the Water Framework Directive (2000/60/EC) and its daughter Directives (2006/118/EC), the Urban Wastewater Treatment Directive (91/271/EEC), the Bathing Waters Directive (76/160/EEC), the Freshwater Fish Directive (2006/44/EC), the Habitats Directive (92/43/EEC) and the EU Sludge Directive (86/278/EEC). Collectively these require significant improvements in water quality standards that can only be achieved with increased energy use[8]

Economic rather than environmental imperatives have until now driven energy efficiency improvements within the water industry. As demand and legislative constraints make such efficiencies harder to achieve, there is a need for new concepts in which the energy contained within water at all stages of the urban water cycle is considered as a resource. For example, thermal energy contained in domestic wastewater predominantly contains heated water from domestic activities that has been mixed with a lesser amount of cooler water. This represents a significant energy recovery option. Figures from Amsterdam show that around 54% of the drinking water that is used by a household is heated and that the average temperature of discharge entering the drainage system is 27^0C[13]. This thermal energy could be extracted via heat exchangers and used to raise the temperature of the cold water entering the premises, as could the thermal energy contained in rainwater.

One route to maximizing energy efficiency and energy recovery opportunities within the urban water cycle; is to optimise the performance of existing systems by drawing on the latest technology. Historic energy usage data within the wastewater treatment process for example, has routinely been kept by water companies simply to provide an insight into the energy efficiency of the plant. The technology and knowhow now exists to optimize such systems by developing real-time multi-criteria energy information platforms that are designed to reduce the consumption of primary energy. This is achieved by maximising energy recovery options and monitoring the energy requirements of wastewater treatment processes on a minute by minute basis.

By recognising that the urban water cycle is not simply a system that transports water from catchment to effluent discharge, but also a potential source of energy, the INNERS project has set itself the challenging goal of proving that an energy neutral urban water system can be a reality.

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2 DRINKING WATER

2.1. The energy balance of drinking water treatment and supply

Drinking water is abstracted from rivers, reservoirs, lakes and streams, i.e. surface water supplies and from groundwater sources such as boreholes. Within England and Wales around 65% of drinking water comes from surface water sources and the rest from groundwater sources[1]. In France an estimated 25% of domestic water is supplied from groundwater sources, with the majority being abstracted from the Paris basin[1]. In Germany the figure is similar at 22%[2]. The way that water is treated to make it safe to drink depends on the source that it came from as both surface water and groundwater supplies contain naturally occurring substances that need to be removed.

Deep well water, i.e. water taken from >30 m, is generally considered to be microbial free. However, it can contain inorganic minerals such as iron, manganese and arsenic radionuclides, as well as other chemicals originating from natural geological formations[3]. Furthermore, interaction with surface water can introduce agricultural run-off or microbial contamination. Conversely surface water extracted from lakes and rivers may be turbid at the point of abstraction and often contains impurities such as silt, algae, micro-organisms and inorganic compounds. It may also contain larger objects such as plant debris. Consequently the stages of surface water treatment are often ordered by the size of the impurities to be removed.

Water entering a treatment plant generally undergoes a six stage process that starts with screening and passes through aeration, clarification, filtration and disinfection before reaching the final stage of pH adjustment. However, in countries such as Switzerland, 47% of the groundwater used is of a sufficiently high quality to be supplied without treatment, 40% is treated by simple methods (usually sand filtration) and only 13% undergoes two or more of the six stages listed above[4].

Energy is used at every stage of the abstraction, treatment and supply process with transportation by pumping representing upwards of 60% of drinking water energy demand[5]. Indeed in the majority of cases, energy consumption is the largest cost in the life cycle of a pump system. This is not surprising when we consider that many pumps in the water supply sector often run for 2000 hours or more per annum [5]. However, assessing the energy needs of drinking water supply systems on a national scale can be difficult due to regional hydrological, geographic, social, economic and legislative differences.

Drinking water systems that rely on surface water are often designed to take advantage of gravity and use little to no energy to extract water from the source and convey it to the treatment facility. Washington D.C. for example relies on surface water taken from the Potomac River[6]. Most of the water is withdrawn at Great Falls Dam and conveyed via gravity to the treatment plant using little energy during the extraction and transportation process prior to it being distributed to domestic properties. In contrast the provision of drinking water is an energy-intensive process for the city of Memphis, as it relies on groundwater being extracted from aquifers 150 - 200 m deep[6]. The amount of energy consumed in raising groundwater depends on the location of the water source relative to the point of discharge and also on the frictional resistance to flow. Table 2.1 provides examples of the energy required to raise water from a range of depths in California. The table clearly shows how the distance that water is raised dictates the amount of energy consumed. The examples presented translate to a specific groundwater pumping energy use value of 0.004 kWh/m^{3}m.

Table 2.1: Examples of energy consumption ranges for raising groundwater[3,6]

Lift (m)	kWh/m^3
35	0.14
46	0.18
61	0.23
120	0.53
172	0.69

The quality of the abstracted water also impacts on the amount of energy needed for treatment, with higher-quality water containing fewer contaminants and therefore, requiring less treatment than lower quality water. For example, treating groundwater uses significantly less energy than treating surface water (typically 0.0024 kWh/m^3 versus 0.38 kWh/m^3)[3]. This is because groundwater is usually of a higher quality and often only undergoes chlorination. Table 2.2 shows examples of energy consumption ranges for conventional water treatment. The large variations relate to the methods of treatment applied and the size of the treatment plant. In the case of Canada, high energy membrane processes such as ultrafiltration are used, whilst in Spain reverse osmosis techniques are employed to desalinate a proportion of the drinking water[3].

Table 2.2: Energy usage ranges for conventional water treatment in a number of countries[3]

Country	kWh/m^3
Australia	0.01 – 0.2
Taiwan	0.16 – 0.25
USA	0.18 – 0.47
New Zealand	0.15 – 0.44
Canada	0.38 – 1.44
Spain	0.11 – 1.50

The energy demand of pumping is significantly affected by the topography over which the water must be moved to deliver it to customers. For example, San Diego acquires a large amount of its water from northern California. Transporting this imported water is energy intensive as it must be conveyed hundreds of miles and lifted 600 m over the Tehachapi Mountains. Furthermore, because of the hilly terrain in some parts of the city and the great expanse over which the customers are distributed, additional energy is required to pump water to its point of use[3]. Table 2.3 provides examples of the energy consumed per unit (m^3) per km when pumping treated drinking water[3]. The total energy used is also included.

Table 2.3: Energy consumed in pumping treated drinking water per kWh/m^{3}km

Catchment	Distance (km)	Energy used per km (kWh/m^{3}km)	Total energy used (kWh/m^3)
California (West Branch)	502	.004	2.01
California (Coastal Branch)	457	.005	2.28
Colorado to Los Angeles	389	.004	1.55
Water Pipe – Australia	450	.007	3.15
Spain	744	.005	3.72

The age of a system and the condition of its pipes and equipment is also known to impact on the energy demands of both drinking water and wastewater treatment services. Specifically, older systems can be less energy efficient if the equipment and infrastructure have not been properly maintained. In 2009 the American Society of Civil Engineers graded America's drinking water and wastewater infrastructure as a D minus[7]. Their assessment noted that "many of the country's systems contain facilities that are nearing the end of their useful lives and that upgrades are required to reduce leakage, which in some areas is as much as 50%". This figure is in keeping with the global average of 25-50% and mirrors the situation in London, where in 2005 it was estimated that more than half of the aged 16,000 km of water pipes beneath the streets had burst. At that time London had one of the leakiest water systems in the developed world[8] with daily drinking water losses of nearly 900,000 m^3.

In addition to location-specific factors, the complexity of some urban water systems can make assessing the energy demands of the urban water lifecycle challenging. For example, urban water systems such as those in San Diego are highly complex as they involve a number of different entities that have responsibility for different parts of the system. Specifically, the City of San Diego currently imports 85 to 90 percent of its water from the Colorado River and northern California[3]. However, its regional drinking water systems are managed by a number of different organizations spread over 400 square miles. This makes collecting consistent data on the water-energy nexus very difficult. The USA is not unique in this respect as many of the examples given above apply in Europe.

2.2. Energy and Leakage

In 2009/10 water companies within England and Wales used 9012 GWh/year in energy, of which 586 kWh was used to supply and treat each megalitre (i.e. 0.586 kWh/m^3), of drinking water[9]. During the same reporting period the total loss of water through the supply network due to leakage was reported by UK Water as being 4251 Ml/day[10]. This equates to an associated energy loss of 909.24 GWh/year or approximately 10% of total energy used annually by the industry.

Within their Supplementary Briefing Note (BNWAT07) the Energy Savings Trust[12] state that 0.34 tonnes of CO_2e were produced for every megalitre of freshwater supplied. When this figures is applied to the daily leakage rate it can be seen that during 2009/10 over 500,000 tonnes of CO_2e were emitted producing water that never made it to the customer. Interestingly, the leakage reduction targets that OFWAT has set the UK water industry only require a reduction of 3.57% to have been made by 2014[13]. That said, it is important to acknowledge the substantial investment in leakage reduction that the UK water industry has made over the last decade, which has seen leakage from their network decrease by 33%. This downward trend is supported by leakage rates reported to OFWAT in 2011, which showed a daily reduction in leakage of 888 Ml/day[13]. Furthermore it should be acknowledged that the UK is not the only European country with an aging water infrastructure. Leakage loses of drinking water for 2007 reported in the 2011 Profile of the German Water Sector[14] show daily fresh water loses for the Netherlands, Austria and France as 7%, 11% and 20% respectively. In all cases the lost water will have consumed large amounts of energy during the associated production process.

2.3. Minimising leakage

None Revenue Water (NRW) is the term that is commonly used to describe water that has been produced and is "lost" before it reaches the customer[15]. It applies to both actual physical losses, such as those incurred through leaks, and to apparent losses that occur as a result of metering inaccuracies or theft. Accounting for water is an essential step towards ensuring that a water utility is sustainable. This is best accomplished when water providers meter use by their customers. Metering helps identify losses due to leakage and also provides the foundation on which to build an equitable rate structure that ensures adequate revenue to operate the system. In England and Wales around 35% of domestic customers have water meters[15]. This means that more than half the population has no connection between the amount of water they use and the size of their water bills. It also means that the utility companies have no effective way of accurately benchmarking leakage within the supply network. Projections are that by 2015 over half of the residential properties in England and Wales will be metered and that by 2030 that figure will have risen to around 80%[16].

2.3.1 Economic Level of Leakage

Since the turn of the 21st century utility companies have increasingly argued that leakage is at economic levels. However, regulators question whether the degree and duration of any flattening out has been justified and argue that the Economic Level of Leakage (ELL) can reasonably be expected to fall further in the long term[17]. Companies have traditionally made this evaluation based on their internal (private costs), but more recently the analysis has been extended to include externalities such as social and environmental costs and benefits. Therefore the ELL can broadly be defined as 'the point at which the economic, environmental and social costs of water saved by reducing leakage; are equal to the cost of new resources used in managing it'.

There are many uncertainties in estimating the ELL and in reporting the actual level of leakage achieved each year. Even greater uncertainty sits with the social and environmental costs. The UK Environment Agency state that "greater transparency of the approach taken and the results obtained, would give assurance that a full economic evaluation has taken place on a consistent basis and that targets are appropriate"[17]. Furthermore they suggest that water companies should take more account of those cases where the assumptions that they are obliged to make are conservative, and in such circumstances strive for a level of leakage towards the lower limit of the economic range, rather than the mid-point. Utility companies that have a supply deficit tend to include leakage reduction as one option in their analysis to close the gap between demand and resources at least cost. This is referred to as the 'least cost planning' approach[17]. Companies without a supply deficit tend to determine the ELL as a stand-alone exercise and use it as an input to their Water Resource Management Plans. However, it is recognised that for any given network reducing leakage to zero is virtually impossible, especially when we consider that ground movement alone is the factor that influences over a quarter of all leaks[18].

2.3.2 The Water Distribution System

A water distribution pipe is required to maintain sufficient pressure in order to sustain flow during peak demand at the furthest outlet, which is referred to as the 'critical point'. This is generally achieved by keeping the pressure of the supply pumps at a constantly high level, so that the drop incurred as water is consumed along the pipe will not compromise demand at the critical point. However as well as consuming vast amounts of energy this approach also increases the chance of leakage by introducing mechanical stresses that can cause new, system failures. Furthermore if there is already a crack in a pipe then the greater the pressure the greater the leakage. This scenario also comes with an energy penalty, as any leak in the system will require additional energy just to maintain water pressure.

At night when only a relatively small amount of water is demanded, the pressure fluctuations within the system are much smaller than in the daytime. Therefore there is no requirement to keep the system fully charged as long as fire hydrant pressure is maintained. Current thinking is that the pressure in the network should be maintained as low as possible, whilst still satisfying the needs of the 'critical point' at all times. The benefit of this approach is that it reduces the risk of mechanical stress, the rate of leakage and the amount of energy used. Such an approach however requires more flexible pumping systems, such as those that are managed by digital controllers and remotely operated pressure reduction valves.

2.3.3 Managing Loses

The International Water Association's (IWA) Water Loss Task Force identified: Pressure Management along with Active Leakage Control (ALC), which can be defined as a pro-active leakage reduction management procedure designed to identify, monitor, repair and control loses, as two of the primary methods of addressing loses from the system[19]. This section looks at a number of case studies that illustrate the type of potential savings that can be made at the start of the urban water cycle.

2.3.4 Pressure Management

Most pumps used for municipal water supply are of the centrifugal type driven by electric motors. They have complex and unique head/flow characteristics and associated energy efficiency curves. Every pump is designed and manufactured to operate most efficiently at a specific "duty point." The duty point is the point at which the pump produces the required flow at the required head, which it has to overcome. The system curve, which is a graphical means of showing the head required to push a fluid through a system of pipes and fittings, is used to assess how a pump located in the system will perform. By plotting the pump curve on the system curve, the flow rate through the system will be indicated by the intersection of the two lines. In an ideal situation, the duty point is arranged to be exactly the point where the energy efficiency of the pump is at its maximum. In this way the efficiency of the pump operation will be maximized. In practice, however, the duty point is hardly ever located at the Best Efficiency Point (BEP).

The 'Actual Pump Efficiency' curve in Figure 2.1 provides an example of a pump that is not operating at its optimum efficiency. The following factors also contribute to this shortfall.

There will often be more than one pump employed in the abstraction and supply of drinking water in order to achieve the required flow. This results in multiple pumps being attached to a common manifold in order to interact with each other, thereby rendering each of the individual pump curves irrelevant. This situation is further compounded when pumping stations operate together to supply the same network.

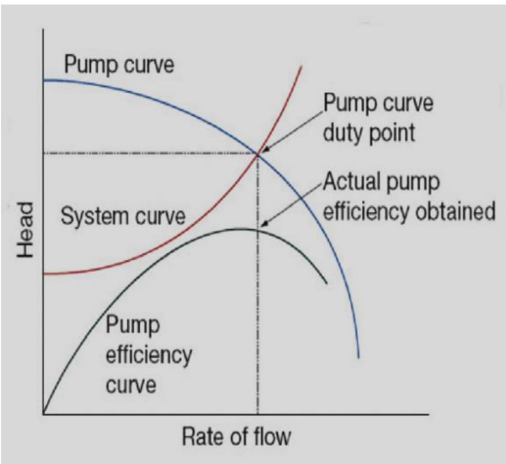

Figure 2.1 – Pump Curves

The location of the pump itself within the pipework can also create inefficiencies as it disrupts the flow creating additional head loss in the delivery system. In addition oversized motors are commonly used to drive pumping systems despite them lowering efficiency and making it impossible for the pump to ever operate at its design curve optimum. The final point to consider is that pumps wear as they get older and as a rule of thumb lose 5% of efficiency within the first 5 years of being installed. After this period they tend to stabilize.

In summary pump performance is subject to fixed and transient head pressures that the pump encounters within the pipe network in which it operates. The impact of all these fixed and transient pressure variables presents designers of pumping systems with a problem when attempting to optimize systems in terms of energy and performance efficiency.

At the time of writing (October 2013) the Water Research Foundation are developing a guidance manual that will allow pump station designers to improve pump wire-to-water efficiency, perform periodic pump efficiency testing, understand the appropriate application of variable speed drives, and evaluate the potential annual energy, cost, and carbon savings from pump station efficiency improvements[20].

2.4. Examples of energy reduction in drinking water supply

The following case studies provide examples of where pump optimization within the abstraction and transportation of drinking water has resulted in significant energy savings.

2.4.1 Optimizing pumping systems to minimise energy usage in the Netherlands

Environmental objectives drove the Dunea Water Company to install a hydraulic connection to manage the flow of water being transported 30 km between Brakel, where it is extracted from the River Meuse and Bergambacht, where it is pre-treated prior to being filtered by the sand dunes. At the Bergambacht intake the arriving water now goes to a small reservoir at the bank of the River Lek. Before the installation of the hydraulic connection the intake at Bergambacht was not harmonised to the input from Brakel, which resulted in around 5% of the distributed water from Brakel draining into the River Lek. Automated control systems now prevent this drainage taking place. This has not only saved a significant volume of water but also an estimated 700 MWh/yr of energy used in pumping it. The hydraulic connection was installed at the same time as planned maintenance activity was taking place on a major dyke[21]. This case study shows that significant energy can be saved even when apparent gravity head differentials are low.

2.4.2 Operational Controls in Germany

The water utility of Suderdithmarschen supplies 28,000 m^3 of drinking water every day in Southern Dithmarschen. The water is taken from 14 wells and is delivered to around 27,000 house connections[22]. Prior to modernization when new pumps and operational controls were installed, six pumps with differing dimensions generated the required pressure of 5.4 Bar. Two of the original pumps had frequency control whilst the rest operated at only one speed. The modernization programme saw all of the aged pumps being replaced with four frequency driven units. This resulted in a 16% energy saving[23].

2.4.3 Variable Speed Drives in the United Kingdom

In order to cover a wide duty-range with a single pump Variable Speed Drives (VSD) should be used. This is because they allow a better efficiency envelope over a large operating range on the system curve. United Utilities opted to change the operational frequency of the pumps at their Pilsworth Pumping station in NW England and made 12% savings against their energy consumption for no capital cost. By reducing the operational frequency of the

VSD by several Hz they were able to reduce the pumping rate from 32 Ml/day to 25 Ml/day[21]. This increased pump operating times but reduced friction head on the system, thereby resulting in year on year savings of 115 Mwh. It is worth noting that where multiple pumps are available the potential for energy gains using VSDs will be reduced.

2.4.5 Active Leakage Control in Australia

Between 2003 and 2008 Sydney Water adopted an Active Leakage Control approach that utilised a combined pressure management, water main renewal and flow meter upgrade programme. This resulted in their daily leakage rate dropping from 188 Ml/day (2002/03) to 105 Ml/day (2008/09)[22,24]. This equated to a 7% reduction in total water loses. The reduction in leakage over the five year maintenance period saved an estimated 6.617 GWh. This figure does not include the fact that the improved flow monitoring system identified valves that were inadvertently open when they were meant to be closed, which resulted in water having to be re-pumped. Sydney Water's Operating License requires that over the period 2010 – 2015 they do not exceed a daily leakage of 105 Ml/day. Interestingly within their Operating License Environment Report[24] they have set themselves the target of maintaining improvements from the Leakage Management Program at or below the Economic Level of Leakage by 2012.

2.5. Supplying drinking water to a large catchment: Yorkshire Water (UK)

In order to provide context to the data provided within this section about the drinking water-energy nexus, Yorkshire Water has been used as a case study.

Yorkshire Water provides water and wastewater services to an area of the UK covering around 12,000 km^2. The area is bounded in the north and west by the Pennine Hills and the North Yorkshire Moors. Annual average rainfall in the area is almost double that of the predominantly low lying southern and easterly regions of the UK.

Yorkshire receives 1400 – 1600 mm of rain per year across the whole catchment. The Rivers Don, Aire, Wharfe, Calder, Nidd and Colne are the largest upland source of water in the district. Between them they provide 33% of the region's drinking water. The remainder is supplied by over 100 impounding reservoirs (45%) and groundwater sources (22%). An additional 21,550 Ml of water per annum is abstracted from reservoirs in the Derwent Valley under an agreement made with Severn Trent Water. This is used to supply the city of Sheffield which is close to the southern extent of Yorkshire Water's geographic limit and within 20 km of the Derwent Valley[26,27]. The total storage capacity of all the supply reservoirs is 160,431 Ml. These water resources are connected by a grid network that enables water to be transferred from one part of the region to another, depending on where it is needed most.

Abstracted water is treated at one of 83 treatment works before being pumped through approximately 3,000 km of clean water pipes to 2 million homes, who between them consume 731.37 Ml of drinking water every day (2007/08). Daily per capita consumption is reported to be 147 litres[28]. Within Yorkshire Water's (25 year) Management Resource Plan[29] is the projection that that by 2035 the region's population will have grown by approximately 700,000, thereby placing an additional demand on water supplies of around 84 Ml per day. They also forecast an expected increase in household demand due to climate change of between 0 – 1.04% by 2035. These figures are based on 2007/08 consumption rates.

The inextricable relationship between water and energy within the water industry is clearly not confined solely to the treatment and supply of drinking water, but spans the whole of the urban water cycle. Therefore it is worth stressing that the figures presented within this section do not reflect Yorkshire Water's total energy usage, or the significant steps that they have taken to generate renewable energy at the wastewater treatment end of the cycle. Table 7.8 of their Water Resource Management Plan[29] shows that 477,496.65 Ml of drinking water was put into the supply system in 2006/07, i.e. 1308.21 Ml/day and that 96.4% of all of the energy used in water supply treatment and pumping came from electricity. By using the UK industry mean of 586 kWh per 1 Ml[9]of drinking water treatment and supply it can be determined that the supply of drinking water, which includes distribution and process losses, consumed approximately 279.8 GW/h of energy, an estimated 167 GW/h (i.e. 60%) of which was used in pumping.

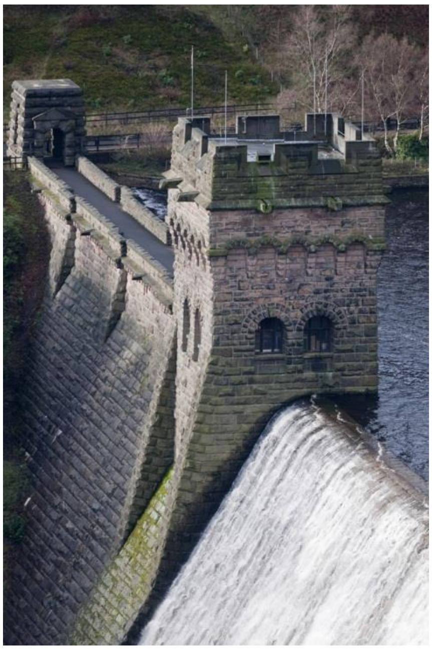

Figure 2.2 – Derwent Reservoir

Between 2006 and 2011 Yorkshire Water lost an average of 300 Ml of drinking water every day[27], which will have required 175.80 MWh of energy to treat and supply. This daily loss is approximately 5 times the amount of water abstracted on a daily basis (59.04 Ml), from the Derwent Valley, which is used to supply the city of Sheffield.

In 2009 Yorkshire Water reported that Active Leakage Control accounted for 20% of their annual supply pipe repairs[29]. It is therefore not surprising that they take leakage control seriously. In order to address this problem they have set themselves the goal of reducing the current leakage target of 297 Ml/d set by OFWAT, by up to 45 Ml/d. This will be achieved by implementing leakage reduction measures in 5 Ml/d phases. Each phase will take a year to complete with additional annual 'find and fix activity' required to maintain the savings.

Yorkshire Water also intend to implement three mains replacement / re-lining phases that are aimed at reducing leakage, by targeting pipes considered to have the greatest potential to leak. The estimation is that each phase will reduce leakage by an additional 5 Ml/d and will take two years to implement. Additional Active Leakage Control activities planned by Yorkshire Water include monitoring supply pipes located within customer boundaries (potential savings 1.2 Ml/d) and implementing leakage zone optimization and pressure management strategies that could yield a further 3 Ml/d reduction. Collectively these measures will have a significant impact on environmental costs of leakage and also on the balance sheets of the company.

2.6. Summary

This section has examined energy used in the production and distribution of drinking water. By using a range of examples it has shown how the amount of energy used within abstraction and supply is highly contingent on local geographic, climatic and hydraulic conditions. A review of the available literature has also identified that the abstraction of groundwater is a more energy intensive process than the abstraction of surface water, the latter of which is often transported by gravity. In relation to water treatment this section has identified how the energy usage for conventional water treatment varies across the developed world and is a function of the purification processes being applied.

The results of this section are collated in Table 2.4, which shows the mean energy in kWh/m^3 for this stage of the water cycle. Where reliable data are missing, known averages relating to the percentage of energy expended on pumping have been used to determine energy values for water treatment, pumping and supply. The figures shown in bold have been taken from the source material referenced. The rest have been calculated as explained.

Table 2.4: Mean energy used in drinking water abstraction, treatment and supply (kWh/m^3) for a number of developed countries[3,5,9,28]

	SE	**GB**	**NL**	**NO**	**AT**	**DE**	**BE**	**DK**	**FR**	**LU**	**STDEV**	**Mean**
Treatment	**0.12**	**0.24**	**0.11**	0.17	0.24	0.24	0.17	0.24	0.24	0.24	0.05	0.20
Pumping	**0.24**	**0.35**	**0.39**	0.24	0.39	0.39	0.24	0.39	0.39	0.39	0.07	0.34
Total	**0.36**	**0.59**	**0.5**	0.41	0.59	0.59	0.41	0.59	0.59	0.59	0.09	0.52
% pumping	**66**	**60**	**78**	60	60	60	60	60	60	60	5.79	62.40

Note: Around 60% of the Netherland's drinking water comes from groundwater supplies. This is reflected in the high percentage of energy expended in pumping and the low value in treatment. For all other countries in the table it is assumed that surface water is being treated and supplied.

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3 DOMESTIC USE

3.1. The energy-water balance of domestic hot water

Regulatory measures aimed at mitigating climate change and economic pressures from rising fuel costs are motivating increased energy efficiency both within the residential sector of the developed world and the industrial sectors that service them. In the United Kingdom for example, 32% of the country's annual energy consumption and a similar proportion of greenhouse gas (GHG) emissions are attributable to domestic use[1]. This figure is close to the 2010 average of the EU27, which was 27%[2].

Historically space heating has accounted for the majority of energy used in European homes (around 70%)[3], while water-heating, appliances, lighting and cooking comprise the balance. Figure 3.1 provides a comparative visual representation of domestic usage across the EU for 1990 and 2009.

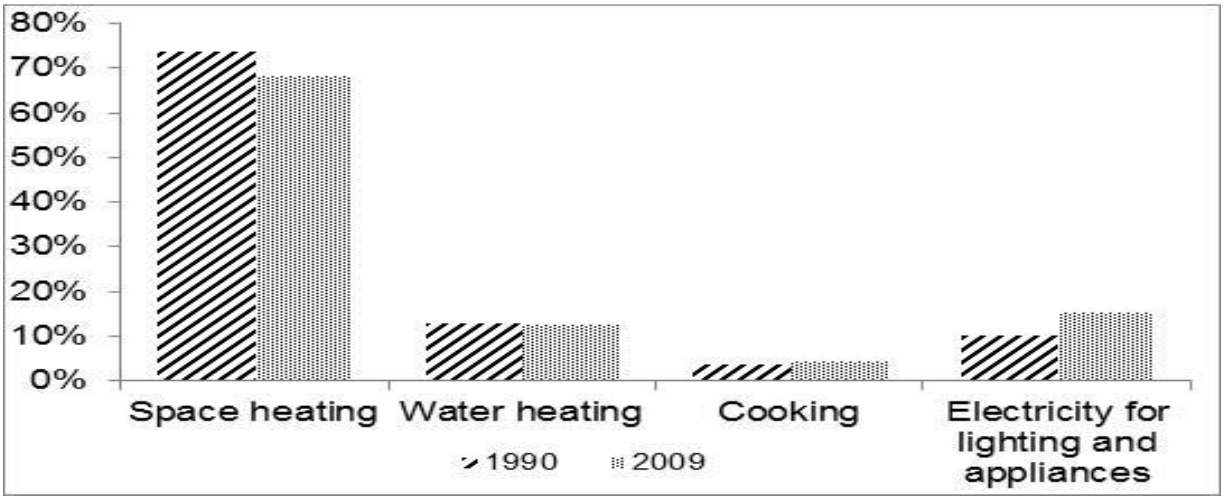

Figure 3.1: Energy consumption by end users: 1990 – 2009[4]

A review at the United Nations Development Programme: Human Development Report 2006[5] shows that there is a significant difference in the amount of per capita fresh water used on a daily basis (litres) between the developed and least developed nations. The USA for example, consumes 575 l/pppd (per person per day), whereas the population of Mozambique struggle to secure 4 l/pppd and fall well below the UN's Water Poverty Threshold (50 l/ pppd). It can also be seen from this report that there is a marked difference in water consumption between many of the industrialised nations with Australia and Japan consuming 493 and 375 l/pppd respectively and Denmark, Germany and the UK consuming 210, 193 and 150 l/pppd respectively.

Table 3.1 shows per capita values for daily water consumption alongside the mean percentage of total domestic energy consumed in heating Domestic Hot Water (DHW).

Table 3.1: Water Consumption versus Energy Demand

Country	Daily per capita water consumption (litres)	% of total domestic energy consumed in heating water
Portugal	161	39%
UK	150	17%
Netherlands	130	50%

From this Table it can be seen that within Europe the amount of energy used for heating DHW varies significantly, whilst the difference in per capita water consumption between the highest and lowest consumer is relatively small (31 l/pppd). There are a number of key factors that help explain this disparity, whilst at the same time identifying opportunities for reducing both energy and water consumption. These are covered in the following sub-sections.

3.2. Hot Water Safety

Mandatory safety requirements for the provision of DHW in the UK are specified in Part G of the Building Regulations[6]. These focus on preventing water boiling anywhere in the system via the use of safety cut-out mechanisms that act independently of thermostatic control. They also seek to prevent scalding from delivery at the tap by requiring mixer valves to be employed. These ensure that the distribution temperature is limited to 60^{0}C and that the water emerging from a bath tap does not exceed 48^{0}C. However, currently there are no European-wide regulations concerning the maximum temperature of domestic hot water at the point of delivery to the consumer, although France and Sweden have laws limiting the maximum temperature of hot water in the home. France specifies 50°C in bathrooms and 60°C in other rooms for all homes and Sweden specifies between 50 – 60°C, with the caveat of 38°C if there is a particular risk of accidents[7,8,].

In other European countries there are only recommendations. Denmark and the Netherlands suggest limiting the water temperature to between 52°C and 57°C at the point of delivery, combined with renewal of the water in the tank 2.5 times each day to prevent bacterial growth. However, it is commonplace in the Netherlands for boiling water to be instantaneously supplied direct to the faucet, and devices designed to do this are currently being advertised within the UK. In Norway 38°C is the recommended limit for hot water within kindergartens and homes for the disabled. Elsewhere 55°C is the suggested limit[9]. More detailed interpretations of the UK law are given in British Standard 8580[10] (2010), which introduces the need for DHW systems to include measures to reduce risks from bacteria and in particular Legionella.

Further information is provided in EU guidelines published in 2005[11]. Balancing the need to prevent scalding whilst keeping water hot enough to control Legionella; is a key requirement of the domestic hot water system. Table 3.2 shows how water temperature impacts on Legionella bacteria[12,13].

Table 3.2: Temperature versus Legionella

Water Temperature Range ^{0}C	Impact on Legionella
70 - 80	Disinfection range
66	Dies within 2 minutes
60	Dies within 32 minutes
55	Dies within 5 to 6 hours
0 - 45	Legionella bacteria multiply
<20	Legionella bacteria are dormant

3.3. Case Study – United Kingdom

Britain's use of energy to provide hot water in homes has fallen dramatically since 1970[14]. Modelling suggests that there has been a fall from 47% to 17% in the proportion of household energy used for heating DHW over the last 40 years. This is consistent with the reduced heat loss from stored hot water as a result of improved lagging, and the gradual elimination of hot water tanks, as combi-boilers have gained in popularity. More efficient heating systems and greater use of showers and dishwashers has also helped bring this figure down. Although this is considered as something of a success story it is set against the fact that over the same period energy consumption of lighting and domestic appliances increased, as did the amount of energy used for space heating, which jumped by 40%. In fact the difference between the outside and inside temperature of homes is considered to be the single most important factor in shaping domestic energy use. The pattern within the UK seems to be that if it is cold outside people opt to heat their homes to around 25^{0}C, whereas if it is mild they opt to heat them to around 18^{0}C[14].

In 2008 the Energy Savings Trust (EST), which is an organisation funded by the British Government and the devolved administrations of Scotland and Wales, carried out a detailed investigation of current patterns of domestic hot water consumption in 120 homes. The purpose of the study was to compare the results with the assumptions of the Building Research Establishment's Domestic Energy Model (BREDEM), in terms of times and temperatures and also to identify where within the dwelling domestic hot water was being consumed[15]. The study showed that the mean household consumption of DHW was 122 litres (± 18 litres) per day. This figure was based on the average between the values recorded from houses fitted with regular boilers (116 litres/day ± 18 litres/day) and houses fitted with combi-boilers, which was 142 litres/day ± 28 litres/day. The mean of 122 litres/day is based on a UK average household occupancy of 2.36 people[16]. This figure is similar to the mean (2.31) of the 2005 occupancy rates for Luxembourg (2.5), France (2.38), Belgium (2.3), Germany (2.09) and the Netherlands (2.28)[17]. The OECD average in 2005 was 2.6 persons per household[17].

3.3.1 Domestic hot-water delivery patterns

Delivery of hot water across the whole of the sample was found to be significantly lower that the BREDEM assumed temperature of 60^{0}C (mean 51.9^{0}C). There was some variation between regular and combi boilers, where mean temperatures of 52.9^{0}C (± 1.5^{0}C) and 49.5^{0}C (±29^{0}C) respectively were recorded. This showed that owners of combi boilers routinely experienced lower hot water delivery temperatures than those with regular boilers. The average daily heating time for regular boilers was found to be 2.6 hrs (± 0.35 hrs). This measure did not apply to the 'on-demand' combi boilers.

3.3.2 Cold water feed temperatures

BREDEM is based on a 50^{0}C temperature change taking place between the external cold water input (10^{0}C) and the point of demand, where it is assumed to be delivered at 60^{0}C. However the Energy Savings Trust's study found this difference to be significantly lower at 36.8^{0}C, which meant that the assumed input temperature of 10^{0}C was an underestimation. This interpretation was confirmed by the recorded cold water feed temperatures which had a mean value of 15.2^{0}C (±0.5^{0}C), i.e. 5.2^{0}C higher[16]. Interestingly this mean value is 2.7^{0}C higher than the average input temperature in the Netherlands, which is 12.5^{0}C[18].

For regular boilers the cold water feed temperature was 16.2^{0}C ± 0.6°C but for combi boilers it was 13.4°C ± 0.6°C[16]. The reason for this difference is that regular boilers take water from a cold water tank that has been slightly warmed by the ambient temperature of the house, whereas combi boilers take their supply directly from the incoming cold main. Thus although the cold water inlet temperatures are not under the control of the householder, and therefore cannot strictly be considered to be part of the hot water use pattern, they do play a vital role in determining the temperature rise required from the hot water system, and hence the energy content of the delivered water.

The Dutch Drinking Water Directive (2001) requires that the temperature of water within the Drinking Water Distribution System (DWDS) should not exceed 25^{0}C. This value is also recommended by the World Health Organisation (WHO) in order to limit the regrowth of micro-organisms[19]. Blokker[20] reports that this is an important fact within the Dutch urban water cycle, as drinking water is distributed without the additional disinfectant that is used elsewhere to manage such regrowth.

Within her report about modelling temperature in the DWDS, Blokker explains that in addition to the legislative measures mentioned, the water temperature is important for a complex variety of physical, chemical and biological processes. For example a temperature increase from 10 – 20^{0}C causes a decrease in viscosity of H_2O of around 30%, thereby requiring additional energy to be used by the pumping system. She also explains that temperature affects chemical processes such as chlorine decay, which is speeded up by a temperature increase, disinfection efficiency and the formation of disinfectant by-products that are harmful to humans[21], biological processes such as the formation of bio-films and physical process such as the absorption of chemicals, contaminants and pathogens.

It would therefore be optimum if the temperature of the water within the DWDS could be maintained at a level that satisfies the myriad of quality, health and energy efficiency requirements. However, it is subject to environmental factors that are likely to become more extreme as the climate continues to change. This is because the temperature of the soil, in which the water infrastructure is buried, is influenced by meteorological conditions such as atmospheric temperature, radiation and environmental factors such as the soil’s thermal conductivity and heat capacity.

The water in the DWDS approaches the soil temperature with a rate that depends on the flow velocity and the water mains heat conductivity. In practice the heating time required for the drinking water to reach the soil temperature is shorter than the residence time of the fluid in the DWDS. It is therefore likely that due to climate change the statutory maximum temperature of 25^{0}C will be exceeded more frequently than in the past for water stored in both the buried and surface storage infrastructure. This interpretation is of course subject to geographic variations, with temperature increases being greater in mainland Europe than in Scotland, for example.

3.3.3 Conclusions of the Energy Savings Trust Study

The mean household consumption was found to be 122 (±18) litres/day. Statistical analysis of the flow data from each dwelling considered the impact of geographical region, boiler type, number of occupants and the number of those occupants that were children. It revealed that the only variable that influenced consumption was the number of occupants.

The mean energy content of the domestic hot water consumed was established to be 16.8 ± 2.2 MJ/day. The energy content of hot water delivered was subject to the same statistical analysis as the flow data and was also found to be solely dependent on the number of occupants. The key recommendation of the authors of the study was that any future model that seeks to determine domestic hot water energy use should include the temperature rise between the incoming and output temperatures, the number of occupants within a household, the region and time of year and the boiler type, as the key variables.

3.4. Summary

By using the findings of the Energy Savings Trust study it has been possible to arrive at an estimation of the amount of energy used to heat $1m^3$ of domestic hot water within the UK. The following rationale has been applied:

- The energy required to heat $1m^3$ of domestic hot water from its mean inlet temperature of 15.2^0C to its mean outlet temperature of 51.9^0C (i.e. an increase of 36.7^0C) is determined using the following calculation: (4186 J/kg^0C) (1000kg) (36.7^0C) / (3.6×10^{-6}) Joules = 42.67 kWh/m^3.
- By using the known daily rate of DHW consumption of 122 litres/day per household it can be determined that it will take 8.2 days to consume 1 m^3 of hot water, making the energy consumption 5.20 kWh/day per household.

The key to reducing the amount of energy consumed to heat DHW is to increase the freshwater inlet temperature, decrease the temperature of the hot water at the point of use, and reduce overall demand.

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4 WASTEWATER

4.1. Water-energy balance of wastewater transportation and treatment

All fresh water that is not retained by the end user is discharged into the sewer system as either 'grey water' or 'black water'. The term grey water refers to wastewater generated from domestic activities such as bathing, washing clothes and dishes for example, whereas the term black water refers to wastewater that contains faecal matter and urine (i.e. raw sewage). Once discharged into the sewer the effluent is transported to the wastewater treatment plant (WWTP) where solid materials such as sand and grit, organic matter and other pollutants are removed. The treated effluent (clean water) is then discharged into a river where it re-enters the natural water cycle.

Pumping accounts for between 20 – 30% of all energy used within this stage of the urban water cycle[1]. However, the amount of energy used in pumping is highly dependent on the availability of gravity to move effluent through the system and the topography and distances involved. The latter of which vary significantly from one catchment to another. Furthermore the systems for collecting, treating and disposing of municipal wastewater vary widely in terms of the equipment and processes used. In the developed world it is common for effluent to go through as many as three treatment stages (i.e. primary, secondary and tertiary treatment[2]), before it is clean enough to be discharged to a water course.

Untreated sewage contains organic matter comprising carbohydrates, proteins and lipids, plus bacteria and chemicals that could be broken down by the naturally occurring bacteria contained within surface water. However, this process can only occur by utilizing the dissolved oxygen present in the fresh water thereby leaving too little to support aquatic life[2], hence the need for appropriate wastewater treatment facilities and processes.

4.1.1 Primary Treatment

During primary treatment the wastewater is screened to remove inorganic suspended solids and to filter out large debris prior to it passing through a grit removal system that enables the particulate matter to be separated out. Following preliminary screening and settling the solids are removed via a process of sedimentation, where they may be disposed of through landfill or incineration, or converted into a tradable product such as fertilizer. It is worth noting that material that is converted into a product, such as compost or fertilizer, is no longer covered by the EU Laws pertaining to waste, but by the (Registration, Evaluation, Authorisation and Restriction of Chemicals Regulations – EC No 1907/2006 (REACH[3]).

Plappally and Lienhard (2012)[4] report that around 60% of suspended organic solids and approximately 30% of Biochemical Oxygen Demand (BOD) is removed in the primary sedimentation tank. They also report that primary treatment is essentially a low energy intensive process and that as little as 0.008 – 0.01 KWh/m^3 of energy is expended in the sedimentation process[5].

4.1.2 Secondary Treatment

Following primary treatment wastewater containing colloidal organic impurities such as proteins and dissolved organic matter, goes through a secondary treatment process that utilizes a combination of physical and biological treatment measures. Of the two, biological treatment of activated sludge, which relies on oxygen dependent micro-organisms to break down the organic matter, predominates. In order to ensure that sufficient oxygen is available to speed up the digestion process blowers and diffusers are used to aerate the waste by injecting oxygen into the wastewater. This is the most energy intensive phase of the wastewater treatment process and typically accounts for around 60% of all of the energy used within diffused aeration secondary treatment systems[1,5]. Within the USA the average consumption of mixing and pumping action at this stage of the treatment process for a 1000m^3 treatment plant is reported by Plappally and Lienhard[4] to range from 0.012-0.033kWh/m^3. Whereas the average energy used in secondary wastewater treatment across the USA[6] ranges from 0.16-0.45kWh/m^3.

4.1.3 Current volumes of sewage sludge within the EU

In 2012 the population total for all of the EU27 countries was 503.71 million people. Projections for 2030 see this figure rising to 520 million before reducing to around 506 million in 2050. Table 4.1 has been included in an attempt to provide some context as to overall volumes of sludge currently being processed by 6 member states (2002 – 2009[,7,8,9]). The figures have been taken from a number of EUROSTAT records and relate to the accumulated settled solids separated from various types of water, either moist, or mixed with a liquid component as a result of natural or artificial processes.

Table 4.1: Percentage of population connected to WWTP and total sewage sludge produced for a sample of EU countries.

Country	2010 Population size (millions)	% of population connected to urban wastewater collection systems	% of population with at least secondary sewage treatment	Total sewage sludge production from urban wastewater (million kgs) ^{e}denotes estimated values
BE	10.84	88	71 (2008)	140^e (2008)
DE	81.80	96	95 (2007)	2049 (2006)
FR	64.71	82	79 (2004)	1087 (2008)
LU	.50	95	88 (2003)	13^e (2008)
NL	16.57	99	99 (2008)	353 (2008)
GB	62.0	99	99 (2002) *	1761 (2009)

* Great Britain data obtained from the UK Department for Environment, Food and Rural Affairs (DEFRA)[10].

4.1.4 Tertiary Treatment (advanced wastewater treatment)

Once most of the organic material has been removed by secondary treatment the carbonaceous biological oxygen demand (BOD) is significantly reduced. This stage of the wastewater management process coincides with nitrogen becoming the main centre for Chemical Oxygen Demand (COD). During tertiary treatment the remaining proteins are broken down to amino acids by autotrophic microbes and further degraded by de-animation to ammonia, which in turn is oxidized to nitrate[4,11]. Following tertiary treatment, which culminates in the wastewater being disinfected, the treated water is discharged into a water course.

4.1.5 Energy consumption within wastewater treatment

The US Environment Protection Agency (2008) report that advanced water treatment with nitrification consumes energy in the range 0.40-0.50 kWh/m^3. This is comparatively higher than the primary and secondary stages. The volume of the wastewater treatment plant plays a significant role in determining the energy requirements for the wastewater treatment processes[12]. As the capacity (volume) of the treatment plant increases, the overall energy consumption of individual processes diminishes. This is evidenced by Japan, where the relatively small size of the decentralized wastewater treatment plants uses between 0.39-3.74 kWh/m^3 for advanced wastewater treatment[13]. Table 4.2 shows typical energy use values for wastewater treatment process within the USA.

Table 4.2: Typical energy use values for WWT processes in the USA (kWh/m^3)[14,15,16].

Process	Energy range KWh/m^3	Average KWh/m^3
Trickling filter	0.09 – 0.29	0.19
Activated sludge	0.18 – 0.42	0.35
Advanced treatment	0.33 – 0.60	0.40
Advanced treatment with nitrification	0.4 – 0.50	0.50

4.2 Storm water and infiltration

The amount of energy and the height lifted within the wastewater system is a function of the volume of liquid being transported along the system and the amount of effluent being treated at the WWTP. This figure fluctuates significantly during times of flooding and heavy rainfall as is evidenced by the German water industry, which in 2011 handled 10.1 billion m^3 of wastewater. Nearly 5 billion m^3 of this huge load was a mix of storm water and excess ground water that had either entered the combined sewer system via roadside gullies and drains, or through infiltration, i.e. via damaged drainage infrastructure[17].

A majority of Europe's sewerage systems are made up of combined sewers that carry both foul water from homes and businesses as well as rain water that lands on paved areas and roofs. Usually waste water in sewers travels directly to a WWTP before eventually being pumped back into a river or the sea. During significant rainfall events however WWTPs are often unable to cope with the increased load, which can often be as much as three times the normal 'dry' operating volume; and the pressure is reduced by means of Combined Sewer Overflows (CSOs). These are designed to act as emergency discharge valves that divert heavily diluted untreated sewage directly into a watercourse, thereby preventing flooding to properties, roads and the WWTP.

Excessive inflow, including infiltration, into a combined sewer system can significantly increase energy usage by a water treatment facility, which in turn inevitably leads to increased costs for the consumer. Reducing the amount of 'clean water' entering this stage of the urban water cycle is the prime role of Sustainable Urban Drainage Systems (SUDS) and also a key component of the EU Soil Sealing Guidelines[18].

4.3. Summary

A review of the literature pertaining to the amount of energy used within the treatment of wastewater has shown that a significantly lower proportion is used in pumping than is used within the abstraction and supply of drinking water. It has also shown that relating energy use to the volume of water being treated only provides part of the picture as it is important to consider the type and stage of treatment being supplied. Table 4.3 shows the mean energy in kWh/m^3 for this stage of the water cycle. Where reliable data are missing, known averages relating to the percentage of energy expended on pumping have been used to determine energy values for water treatment, pumping and supply. The figures shown in bold have been taken from the source material listed. The rest have been derived by means of a regression analysis of the data contained the INNERS Benchmark Report (2013)[20].

Table 4.3: Details the average energy (kWh/m^3) consumed in pumping and treating wastewater[4,5,19, 20].

	SE	**GB**	**NL**	**NO**	**AT**	**DE**	**BE**	**DK**	**FR**	**LU**	**STDEV**	**Mean**
Pumping	**0.06**	**0.12**	**0.11**	0.14	0.3	0.05	0.05	0.1	0.14	0.07	0.07	0.11
Treating	**0.5**	**0.51**	**0.48**	0.59	0.3	0.23	0.22	0.42	0.6	0.28	0.14	0.41
Total	**0.56**	**0.63**	**0.59**	0.74	0.33	0.28	0.27	0.52	0.74	0.35	0.18	0.50
% pumping	11	20	20	20	10	20	20	20	20	20	4.92	18.10

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5 DISCUSSION AND CONCLUSIONS

A review of literature drawn from a broad range of academic, water-industry, national government and EU sources, has shown establishing energy use values for each stage of the urban water cycle to be a problematic process. This is largely down to the fact that the necessary information either does not exist, or is widely distributed and often inaccessible. The only country for which data was available across all stages of the urban water cycle was the USA. In all other cases generic values for one or more of the variables that comprise the cycle have had to be used.

The production of DHW accounts for around 85% of all of the energy consumed within the urban water cycle as described within this review. By increasing the input temperature of cold water by 1°C and reducing the output temperature by the same amount, the energy used in producing 1 m^3 DHW could be reduced by 2.26 kWh. When applied across the European Union the potential energy, cost and CO_2 savings of this simple action are immense.

DHW has been omitted from Figure 5.1 to enable the national values for water supply and disposal services to be viewed separately.

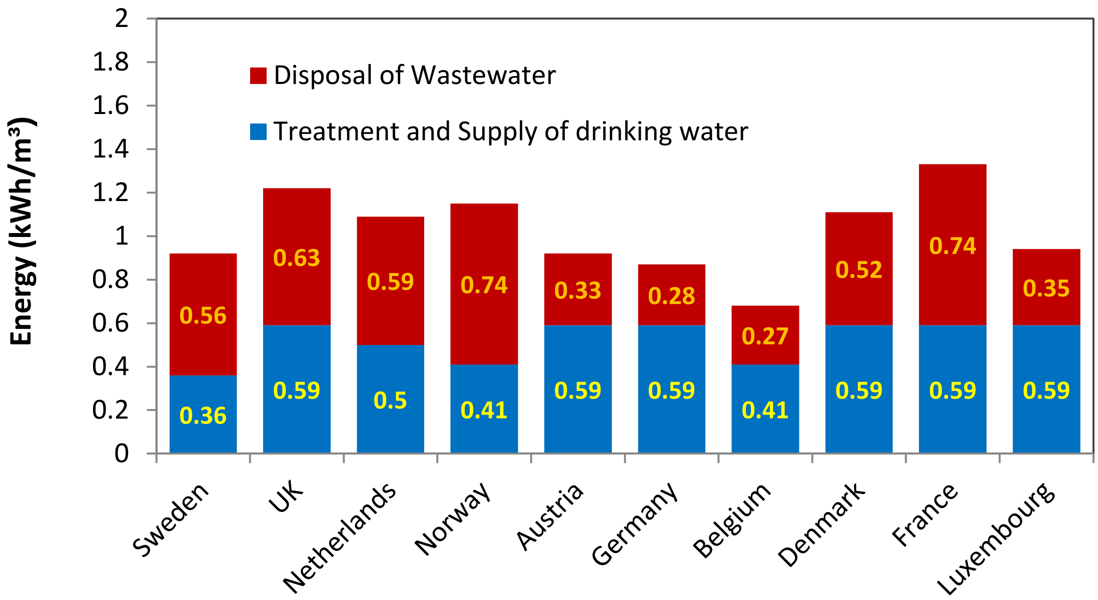

Figure 5.1: Comparison of the energy used to abstract, treat and supply drinking water and the energy used within the wastewater treatment process.

By reviewing the current state-of-the-art relating to all aspects of the urban water cycle it has been possible to identify where options for making energy savings and recovering energy from within the system exist. In the case of drinking water supply the potential for energy savings are to be found in pump optimization and active leakage control, rather than in any of the treatment processes. Systems such as heat exchangers that capture the thermal energy of rain water and ground source heat pumps are two technologies that can be used to raise the cold water input temperature.

Opportunities for extracting energy from wastewater are more abundant than during the drinking water supply stage. Options include exploiting urban organic flows to recover both material and energy. This approach uses co-fermentation of black water with bio-mass from waste to produce methane that can be utilised for energy production in a combined heat and power (CHP) plant. An alternative method is to pump sewage through heat exchangers to provide community heating and hot water, or alternatively to install the heat exchangers in the sewer pipes. In the latter case fouling of the heat exchangers is a constant problem, although there are technologies available, such a vertical screw systems that significantly reduce fouling by non-organic matter.

This literature review extends beyond the current state-of-the-art by introducing domestic hot water into the energy balance of the urban water cycle. However, whilst it provides a comprehensive overview of the system, the values for most of the European countries remain indicative.

Acknowledgements

During the course of this review around 150 documents and on-line resources were reviewed in an attempt to present a balanced appraisal of energy and the urban water cycle. Eighty two of which have been cited within this document. Of these, two sources in particular have been used extensively and it is felt appropriate that these should be acknowledged here. These sources were: ‘Energy requirements for water production, treatment, end use, reclamation and disposal’. Written by Plappally and Lienhard and published in the Journal of Renewable and Sustainable Energy Reviews (2012), and Gustaf Olsson’s appraisal of the water-energy nexus in ‘Water and Energy: Threats and Opportunities, which was published in 2012’.