Intervention concepts for energy saving, recovery and generation from the urban water system

JOS FRIJNS

trust

D45.1

TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

Intervention concepts for energy saving, recovery and generation from the urban water system - D45.1

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2014

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The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265122.

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SUMMARY

Climate change has challenged the water sector to optimise the energy use and limit greenhouse gas emissions of their operations. A review of technological developments and practical experience in the water industry, shows a large potential in energy saving and generation in the water system.

There are numerous options for energy measures in the water sector ranging from water conservation and process efficiency improvements to new technologies and redesigning water systems. Next to energy efficiency improvements, there is a need for new concepts in which water is viewed as a carrier of energy. Municipal wastewater is a potential source of chemical energy, i.e. organic carbon that can be recovered as biogas in sludge digestion. Even more so, domestic wastewater is a source of thermal energy. And in areas with altitude differences, installing micro-hydro technologies in water distribution systems can convert energy from the pressure and flow into electricity.

This report presents intervention concepts for energy saving, recovery and generation from the urban water system. The main outcomes of research undertaken at the following 8 case studies are:

Improving energy efficiency in the Algarve multi-municipal water supply system:

By performing an energy audit the most energy efficient operating scheme can be determined. In the case of Beliche, it was concluded that, in terms of energy efficiency, it is best to have the water treatment plant of Beliche working the whole year and not only at the high season.

The combined application of a new coating in the pumps and a new pumping schedule resulted in a reduction of 12,9% in the total energy consumption of the pumping station and a reduction of 20,3% of the total energy costs .

Energy audit of a water distribution network – Alcoy case study

Performing an energy audit of pressurised water networks, gives a good indication of the energy problems and possibilities and locations for energy saving. In the case of Alcoy, the energy audit revealed that energy embedded in leaks represent 19% of the total energy supplied. Introducing a PAT (pumps as turbines) could result in an energy recovery of 631 kWh/d.

Heat recovery from water and wastewater systems in Oslo.

The thermal energy recovery potential in the water sector is enormous. The highest potential lies within the large-scale examples such as wastewater effluent and recovery directly from the sewer mains, combined with district heating.

In Oslo, heat is already being recovered with a heat pump at the Oset water treatment plant. The potential for heat recovery at the Bekkelaget wastewater treatment plant of Oslo is large, based on a comparison with the current heat recovery system at another WWTP in Norway.

Thermal energy in the water cycle in Amsterdam

Feasibility studies in Amsterdam show that heat and cold recovery from both drinking water systems as well as wastewater systems coupled to aquifer thermal energy storage systems are technically and economically feasible.

Temperature measurements in the sewer system of Amsterdam revealed that the available heat in the sewer could provide for approximately 30% of the required energy to prepare warm tap water in households.

Energy optimisation at Schiphol airport wastewater treatment plant

The energy balance of the wastewater treatment plant of Schiphol airport can substantially be improved by the combined digestion of sludge and fecal deposits from airplanes. Separate treatment of fecal deposit from airplanes, directly to the digester, will increase the biogas production from 17% to 27% of COD influent load. Subsequent autotrophic nitrogen removal and struvite (P) precipitation show positive energy effects.

Integrating pressure and energy management and microgeneration in Langhirano

In a water distribution system, water and energy can be saved by integrating pressure and energy management. Energy can be generated by replacing Pressure Reducing Valves with turbines or installing reversible pumps (PAT).

Modelling results of the Langhirano water distribution network shows that the inclusion of micro-turbines is not in contrast with the measures taken to save water and energy (further pressure reduction and optimisation of pumps operation).

Hydro-generation in the water supply system of Athens

Substantial amounts of energy can be generated by micro-turbines in water distribution systems. Currently, the five small hydropower plants in the Athens external water sypply system generate 20.6 GWh/y.

The available renewable energy potential can be further exploited with additional hydropower plants. Various options were simulated with a water-energy model. The construction of a pump storage scheme seemed feasible. The development of an additional hydropower plant at the outlet of Evinos-Mornos tunnel has the biggest impact on net energy consumption and renewable energy fraction.

Micro-hydro generation in the Algarve multi-municipal water supply system

Generating hydropower in a water supply system is an attractive form of renewable energy. However, these systems are still under development as it has not shown to be cost-effective.

In the Algarve, the Beliche power plant is currently operating, using two pumps-as-turbine to profit from the head in Beliche dam and the flow used in the water treatment plant. A cost-benefit analysis showed that if all O&M costs would be taken into account, the operation of the hydropower plant would not be viable.

1. INTRODUCTION

1.1 Purpose of this deliverable

Water and energy are integrally connected. Water is needed to extract energy and generate power, and energy is needed to treat and transport water. The world's growing population and increased prosperity will put pressure on global demand for energy, as well as on water supplies in the coming decades. Moreover, both resources are needed to grow food. Modern agricultural methods are very energy and water intensive. Shortages could cause social and political instability, geopolitical conflict and irreparable environmental damage. The relationship between water, energy and food is appearing on the agendas of governments, NGOs and businesses. According to the World Economic Forum (2011), the key challenge is to incorporate the complex interconnections of the water-energy-food nexus into response strategies that are integrated and take into account the many relevant stakeholders. Trade-offs will increasingly be needed between energy and water in terms of resource allocation and planning.

Climate change has challenged the water sector to optimise the energy use and limit greenhouse gas emissions of their operations. The focus on energy efficiency measures is very much needed to reduce the carbon footprint of the water sector. Additionally, more substantial improvements will be necessary as it is expected that more advanced and energy intensive treatment will be required to adhere to future demands and quality standards and to adapt to climate change. Future demands require a new integrated approach in the full urban water cycle. New concepts will be needed in which water is viewed as a carrier of energy (organics and heat), and as a source for renewable energy (see figure 1.1).

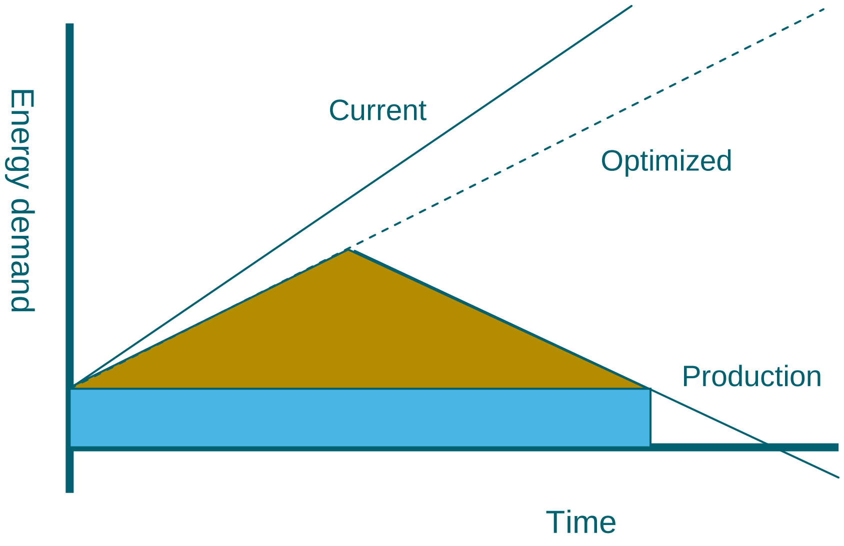

Figure 1.1.1. Energy use over time with and without optimisation and new approaches in the urban water cycle (Source: adapted from GWRC, 2008)

This report describes the intervention concepts for energy saving, recovery and generation from the urban water system. The report is a deliverable (D45.1) from the TRUST task WP45: 'Strengthening the water-energy nexus in urban water systems'. The goal of WP45 is to contribute to the energy self-sufficiency of water utilities by developing innovative technology and management options.

This deliverable, reports on the results of the research activities performed in:

- Task 45.1 The interconnection potential of enhanced water-energy flow synergies
- Task 45.2 Technologies and management options for energy saving in UWCS
- Task 45.3 Technologies and management options for heat and power generation from UWCS

It builds on the reports:

- WP45.1 The interconnection potential of enhanced water-energy flow synergies (internal deliverable, June 2012)
- MS29 Selection of intervention technologies in pilots based on water-energy interconnection potential (November 2012).

Emphasis is put on improving the energy efficiency in all steps and processes of the urban water cycle. The second side of the water-energy nexus, dealing with the necessary progress to manage and use water in a more efficient way (e.g. for energy generation), is not part of this report. No doubt, there is a lot of room to improve in efficiency in water use. Depending on the local circumstances, the priority can be different, e.g. in water scarce regions of South-Europe priority will be on efficient water use.

1.2 Report outline

Chapter 2 presents the review of the potential for energy optimisation in the urban water cycle.

Based on this review, the following options for energy saving and alternative energy recovery and generation concepts in UWCS were selected to be further investigated in selected pilot cities:

- Improving energy efficiency in water supply
    - Optimising the operation scheme, including leakage control, based on an energy audit
    - Improving pump efficiency

- Heat and Power generation from wastewater
    - Enhanced biogas production through co-digestion (combined with P-recovery)
- Heat and cold recovery
    - Heat and cold recovery from drinking water and sewerage
    - Combined with aquifer thermal energy storage
- Micro-generation in water systems
    - Integrating pressure and energy management through energy generation with micro-turbines
    - Hydro power plants in water supply systems and pump-and-storage scheme on aquaduct

The research on these intervention concepts has been performed in the following pilot cities:

Table 1.1. Research topics at the pilot cities

	ALCOY	ALGARVE	AMSTERDAM	ATHENS	LANGHIRANO	OSLO	SCHIPHOL
Energy audit	√	√					
Biogas production							√
Heat recovery			√			√	
Micro-generation		√		√	√		

The chapters 3 till 10 present the research outcomes of the intervention concepts in the pilot cities.

1.3 References

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2. POTENTIAL FOR ENERGY OPTIMISATION IN THE URBAN WATER CYCLE

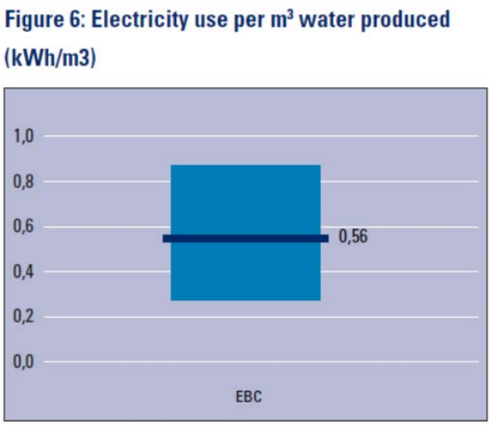
2.1 Energy consumption

The urban water cycle of production of drinking water from ground water or surface water, distribution, consumption, discharge in sewerage to wastewater treatment plants and finally discharge to surface water, consumes energy. In drinking water, the energy use is determined by the treatment process and distribution distances. Pumping can be a substantial part of the overall energy use, depending on the geographical conditions. In any case, the energy use for tap water is substantially lower than for bottled water, as Botto et al (2011) calculated for Italy. In wastewater treatment aeration typically consumes 60% of the energy budget. Through sludge digestion, part of the energy required can be produced at the wastewater treatment plant (WWTP).

The energy consumption in the urban water cycle is increasing. Legislation such as the EU Urban Waste Water Treatment Directive has resulted in additional nitrogen and phosphorus removal practices at wastewater treatment plants (WWTPs) in the EU. Also targeted action against sewer overflows has resulted in more wastewater reaching WWTPs, further increasing energy consumption. The Water Framework Directive aims to achieve 'good' ecological status for all waters and to eliminate pollution by dangerous substances. Elimination of hormones and medicine residues could require the provision of highly advanced energy intensive treatment processes both at drinking water production and WWTP in the near future. Hoibye et al. (2008) estimate an increase of 0.12 kg CO_2 -e/m^3 emissions from additional treatment steps to adhere to the Water Framework Directive. Also, climate change will result in higher energy consumption for drinking water production. Droughts, rainstorms, seawater intrusion, groundwater salinisation, for example, will result in a decline in the availability and quality of water resources. The likely use of alternative sources (brackish groundwater, wastewater) will require energy-intensive treatment processes.

The European Benchmarking Co-operation (2011) recently published the international benchmark of the urban water cycle using data of 2009 from 41 water and wastewater utilities from 21 different countries. The median electricity consumption for drinking water was 0.56 kWh/m^3 and for wastewater treatment was 33.4 kWh/p.e.; ranges are shown in Figure 2.1.

WssTP (2011) reports a range of energy intensity in Europe of 0.5-4 kWh/m3 for drinking water production from surface water resources, and 0.15-0.7 kWh/m3 for wastewater treatment by activated sludge.



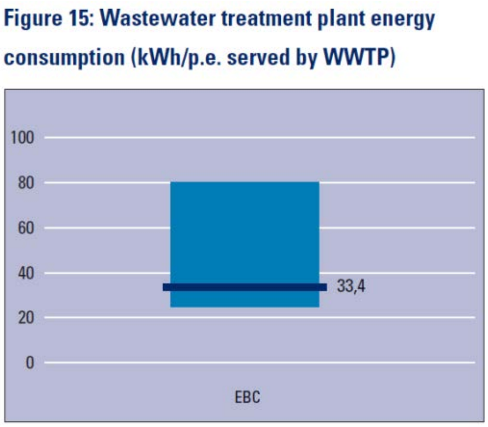


Figure 2.1 Results from the international benchmark, showing the energy use in the water sector (Source: European Benchmarking Co-operation, 2011)

A more detailed analysis was done in the Netherlands, including the energy used in households to heat the water (de Graaff et al., 2011a). This study showed that most energy in the urban water cycle is used for heating the drinking water used for showering, cleaning etc (Figure 2.2). This heat leaves the households through the sewerage and has the potential to be recovered, for example by installing shower heat exchangers. Furthermore, this study showed the differences between two case studies (Amstelveen, a city South of Amsterdam, and Wijlre, in the South of the Netherlands).

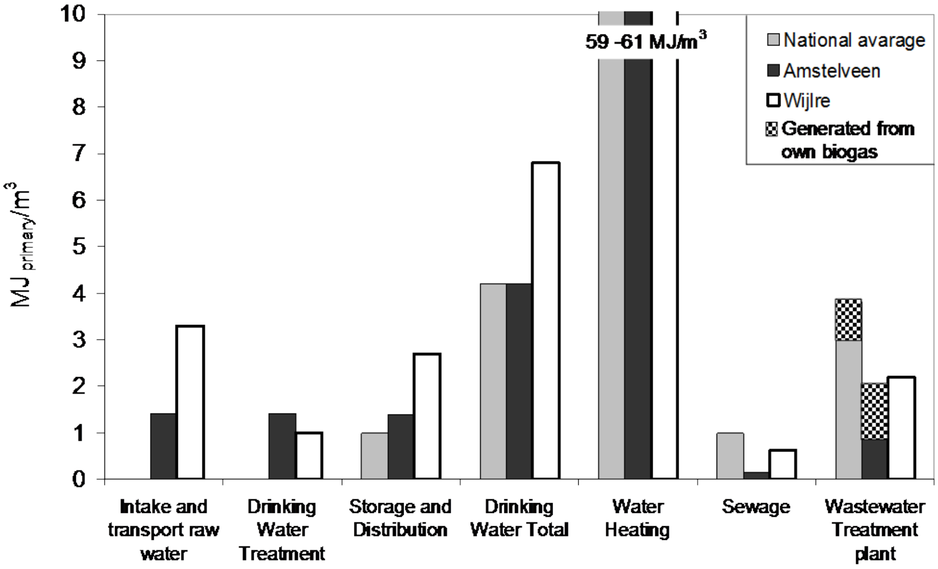


Figure 2.2 Energy in the Dutch urban water cycle (Source: de Graaff et al, 2011a)

Although end use often has the highest energy use of all water sector elements, it has not traditionally been seen as a direct part of the water sector and is often unaccounted for in water management and policy (Rothausen & Colway 2011). Kenway et al (2011a) estimate for a hypothetical city in Australia that the water-related energy use, thus including residential, commercial and industrial purposes, accounts for 13% of total electricity and 18% of the natural gas used by the population on average.

2.2 Carbon Footprint

To estimate environmental impacts and climate change, insight is necessary, not only in the energy use, but also in other direct and indirect emissions such as methane and nitrous oxide emissions and indirect emissions due to the use of chemicals. Carbon footprinting has shown to be as useful tool (Weidema et al. 2008), widely used in several sectors.

The carbon footprint of the Dutch public water sector was projected to be 1.67 million tonnes CO_2-equivalents per year, or 1.5 kg CO_2-equivalents per m3 domestic water (Frijns et al. 2009). The assessment includes CO_2 emissions from energy consumption and methane (CH_4) and nitrous oxide (N_2O) emissions from water treatment processes (based on available emission factors).

The contribution of methane and nitrous oxide emissions to the total carbon footprint of the Dutch water sector appeared to be relatively high: 36% (see figure 2.3).

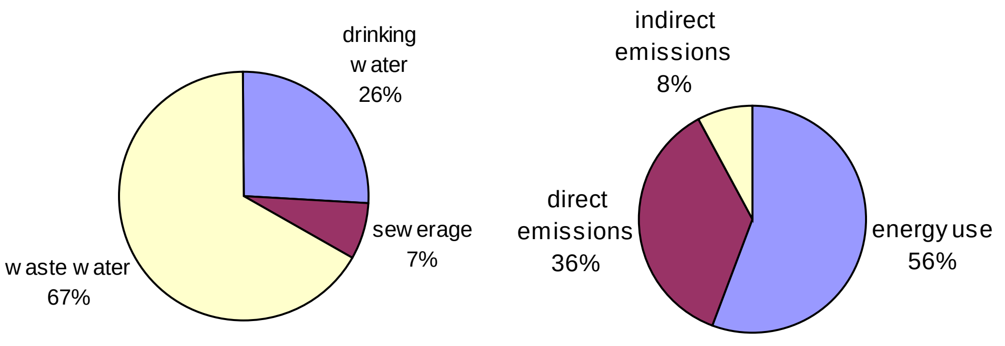


Figure 2.3: Carbon footprint distribution of the Dutch water cycle (Source: Frijns et al 2009)

Several water companies in Europe have estimated their carbon footprint. At the time being, however, carbon footprints of different parts of the water cycle are calculated in many diverse ways, through which it is hard to compare the different processes which are applied throughout the water cycle. There is debate on the amounts and mechanism of methane and nitrous oxide emissions. Next to the lack of common emission factors for greenhouse gases and chemicals used, there is also no agreed upon approach related to the system boundaries and scope of carbon footprinting of the water cycle. Moreover, the greenhouse gas emissions associated with the energy source for electricity production varies between countries.

A major effort has been done in the UK, where the water industry is participating in the development of standardised reporting requirements for carbon footprint analysis (UKWIR 2008). Frijns (2012) proposes a standardised approach for carbon footprint assessment so that quantification can be made in a consistent, robust and auditable manner. Additional information is required to reach agreement on the following aspects for carbon accounting:

- energy use for wastewater transport in sewer systems;
- CO_2 emissions from groundwater;
- CH_4 (and N_2O) emissions from sewer systems;
- N_2O (and CH_4) emissions from wastewater treatment;
- N_2O emission factor for sludge incineration;
- emission factors for chemicals.

It is particularly necessary to more accurately quantify nitrous oxide emissions. The strong greenhouse gas nitrous oxide has a large impact on the carbon footprint even when the amount of nitrogen converted to nitrous oxide is a fraction of a percentage point. Most commonly used emission factor:

$$N_2O\ (wwtp) = 0.005 * N_{kj}\ (influent)$$

However, several recent on-line measuring campaigns for nitrous oxide at full-scale wastewater treatment plants show a large variation in nitrous oxide emission values.

Such a standardised approach should also give consideration to the system boundary and scope, i.e. whether and how the following elements are included in the carbon footprint: renewable energy; long-cycle CO_2 from groundwater; nitrous oxide from effluent discharges; sludge disposal; materials; water use in households; industrial water cycle.

In any case, there is need for measurements of greenhouse gases at full-scale facilities. Measured emissions from the Amsterdam urban water cycle revealed substantially lower and large differences with estimated emissions based on emission factors (de Graaff et al, 2012).

Box 2.1: Carbon footprint of Scottish Water

Scottish water provides drinking water and treats the wastewater for Scotland. Scottish Water has been measuring the operational carbon emissions annually since 2006/2007 and producing a yearly report presenting the operational carbon footprint (available from www.scottishwater.co.uk). The yearly electricity use of Scottish Water is 460 GWh. Electricity accounts for 72& of the operational carbon footprint, which in total is 447,600 tCO_2-eq in 2009/2010 (see figure 2.4).

The methodology that is used is the UKWIR Carbon accounting workbook (CAW, v4.1) based on Defra reporting guidelines (UKWIR, 2008). Emissions from sludge recycled to agriculture land are now allocated to the farmer's carbon footprint, not to Scottish Water's carbon footprint. The indirect emissions due to chemical use are not included in the footprint, but is subject of further UKWIR research.

These data are also used to determine a sustainability indicator to use as benchmark against Water UK sustainability indicators. For Scottish Water, the greenhouse gas emissions from supplying water is 0.17 tonnes CO_2 per m^3 and from wastewater treatment 0.77 tonnes CO_2 per m^3, compared to 0.34 and 0.70 tonnes CO_2 per m^3 respectively for the UK.

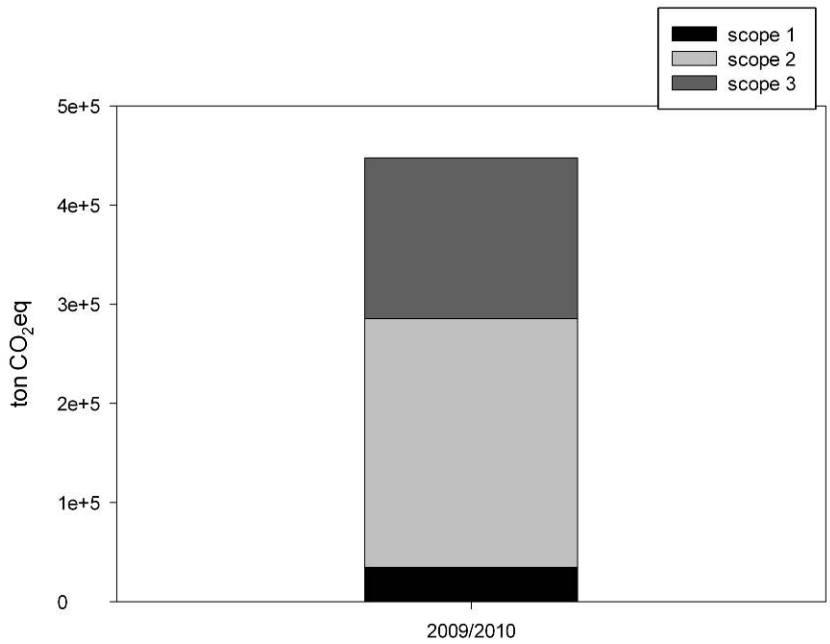


Figure 2.4. Scottish water carbon footprint (Source: adapted from Scottish Water, 2010)

Next to the carbon footprint report, Scottish Water develops yearly a Carbon Plan, describing the plans to mitigate CO_2-eq emissions.

2.3 Energy saving

Water utilities face the challenge of being more energy efficient. After manpower, energy is the highest operating cost item for most water and wastewater companies. High energy consumption will affect the water industry world wide and is inextricably linked to the issue of climate change. Climate change confronts the water sector with the need to optimise the energy use and limit greenhouse gas emissions of their operations (Smith et al. 2009). By doing so, water utilities contribute to the strive by European and national governments for substantial energy reductions in the coming years of up to 20%.

There are numerous options for energy measures in the water sector ranging from water conservation and process efficiency improvements to new technologies and redesigning water systems. Examples of energy measures that are available for actual implementation (i.e. proven technologies) include (Frijns et al, 2012):

- Consumption: (warm) water conservation
- Water distribution system: leakage reduction, optimised gravity flow, pressure optimisation, demand modelling
- Water treatment: energy efficient technologies, e.g. low pressure UV, high yield membranes
- Pumps: efficiency improvements, e.g. duty point and duty rate selection, variable speed drives, inter stage pumping, reduced Returned Activated Sludge pumping
- Sewerage: infiltration and inflow reduction, real time control
- Aeration in WWTP: energy efficient bubble aerators, on line aeration control
- Nutrient removal: ensuring correct sludge age, ammonia derived DO control, separate treatment of reject sludge water for N-removal
- Mixers: high yield equipment, combined mixing with pumping and/or aeration
- UV treatment: enhanced inflow quality, dosing rate variation with effluent quality
- Sludge thickening: low energy equipment (e.g. belts)
- Sludge end treatment: maximum dewatering to reduce drying energy demand

The number of examples of actual implementation of energy measures in water production and treatment is growing rapidly. Drinking water companies have implemented energy-efficient production techniques and optimised distribution systems. As pumps constitute the most part of the greenhouse gas emissions of water distribution systems, particular attention is paid to pump scheduling optimisation (Basupi et al, 2014) and optimised pipe and network designs (Nogueira Vilanova & Perella Balestieri, 2014). Measures that reduce the energy use in wastewater treatment, such as bubble aeration and aeration control systems, are becoming common practice in Europe. Cabrera et al (2010) showed the substantial overall energy saving that can be achieved by leakage control in water distribution networks.

2.4 Energy recovery

Next to energy efficiency improvements in the water sector, there is a need for new concepts in which water is viewed as a carrier of energy (Frijns et al, 2013a). Municipal wastewater is a potential source of chemical energy, i.e. organic carbon that can be recovered as biogas in sludge digestion. Even more so, domestic wastewater is a source of thermal energy. An analysis of the Dutch water cycle showed an energy neutral water cycle is achievable if the thermal and chemical energy content of wastewater is recovered (Hofman et al., 2011). See also figure 2.5.

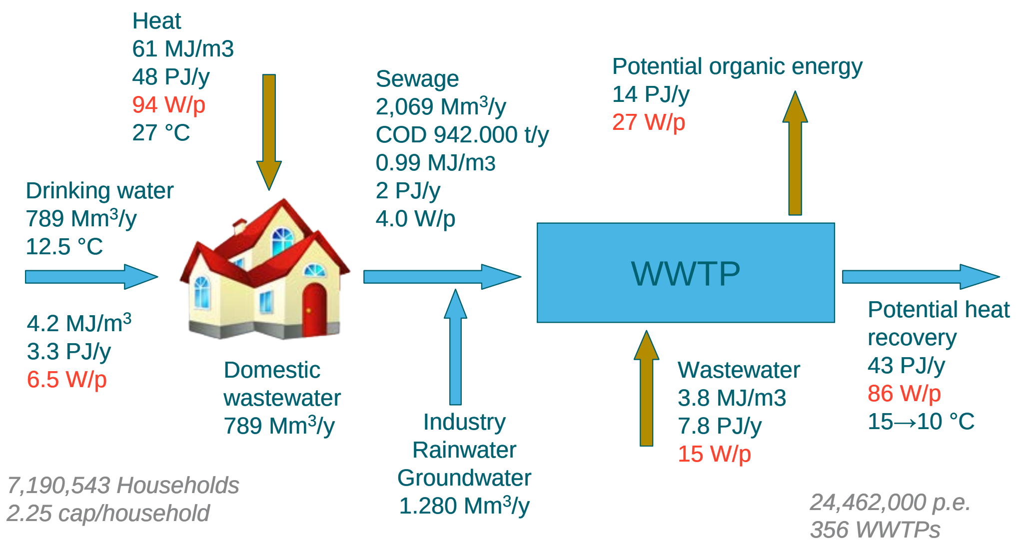


Figure 2.5: Energy flows (input and potential output) in the Dutch water cycle (in primary energy per m³ and year and Watt per person (Source: adapted from de Graaff et al, 2011a and Hofman et al, 2011)

Examples of energy recovery measures (Frijns et al, 2012):

- Maximised digestion by increased primary sludge feed, sludge pre-treatment, high yield gas motor and/or operational improvement (mixing, temperature)
- Biogas combined heat and power (CHP): process optimisation, co-digestion and enhanced biogas conversion and use (e.g. green gas)
- Hydro generation (micro turbines)
- Heat recovery from wastewater at households or from the sewer system
- Energy measures at buildings, and solar energy and wind turbines installed at premises.

Wastewater contains organic energy from the organic pollutants discharged to the sewer system. At WWTPs part of this organic energy can be recovered in the form of biogas from sludge digestion. In this way, in the Netherlands on average 30% of the organic energy in wastewater is recovered in the form of biogas. By using new techniques this can be further increased, turning a WWTP into an energy factory, as is currently being investigated in the Netherlands. Within the Energy Factory initiative, 13 Dutch water boards participate in designing wastewater treatment plants (WWTPs) that not only use as little as possible energy but also maximize their energy production through the recovery of chemical energy in sludge digestion (Kiestra 2010). This would require improved pre-settlement, a higher energy-efficiency of the gas motor, and separate treatment of reject sludge water for N-removal (Sharon-Anammox). An energy producing WWTP could become feasible with the application of fuel cells and sludge pre-treatment (e.g. CAMBI). In future, the project foresees that additional energy production from sludge can be achieved with supercritical gasification.

The recovery of chemical energy can be maximised by up-concentration of organic carbon and maximised sludge digestion (Verstraete et al, 2009) or by source separation and anaerobic treatment (Zeeman et al, 2008, de Graaff et al, 2011b). Also co-digestion at WWTPs can result in an energy self-sufficient operation and even a surplus energy production. To accelerate the digestion and enhance the production of biogas, various pre-treatments can be used. Using for example thermal hydrolysis as a pre-treatment (CAMBI), an increase of biogas production by 150% is reported (Appels et al, 2008). Instead of biogas conversion in a CHP to electricity and heat, the biogas can also be converted to green gas and supplied to the natural gas net.

Even more so, domestic wastewater is a source of thermal energy. Through warm water conservation and heat recovery, for example with shower heat exchangers, substantial amounts of energy can be saved and recovered from the water cycle. The wastewater leaving households has a large potential of thermal energy. On average, the temperature of the water leaving households is 27 °C. Most heat is lost in the sewerage system where most probably the ground is functioning as a heat exchanger, determining the temperature. This has been proven for drinking water systems (Blokker et al, 2013), and is currently under investigation for sewer systems (e.g. Cipolla & Maglionico, 2014). Drinking water distribution systems and surface waters can also be a source of thermal energy. Rather simple measures such as shower heat exchangers save about 30-40% of gas used for showering. Installing a shower heat exchanger at households can save up to 8% on total gas use.

Water can also be an important renewable energy source, i.e. as underground thermal energy storage. These systems are developing rapidly in Europe and its energy potential is large. However, current systems of underground thermal energy storage may have negative effects on the groundwater quality and compromise the natural resilience of the subsurface environment (Bonte et al, 2011). An interesting development is the combination of Aquifer thermal energy storage (ATES) systems with heat from surface water, drinking water or sewer systems. De Graaf et al (2008) demonstrated that ATES supplemented with surface water heat collection in summer, yields sufficient heat to compensate total heat demand of a new residential district.

In table 2.1, the potential of recovering energy from water in the Netherlands is summarised.

Table 2.1. Potential of recovering energy from water (Source: data from KWR)

TYPE OF POTENTIAL ENERGY	POTENTIAL	EXAMPLE IN THE NETHERLANDS
Heat from drinking water distribution system	4.18 MJ/m^3 per degree	Almere
Shower heat exchanger	8% saving in total gas use	For NL: 8% of 1600 m^3 gas = 4.1 $*10^3$ MJ per household
Heat from sewer system	Mainly depends on flow in the sewer, minimum flow of 10 – 12 L/s is required. As a rule of thumb: the heat in wastewater of four houses can provide the heat requirement for one house	In Amsterdam, Watergraafsmeer, sewer system 20 L/s: 391 kW of heat, supplying heat for 195 appartments
Organic energy from wastewater	Max. 10 W/p.e.	Conventional sludge digestion: 30% of organics in wastewater is converted to biogas
Underground Thermal Energy Storage	Max. potential is estimated to be 15,000 – 30,000 TJ/y in the Netherlands	More than 1.000 locations in the Netherlands
Energy production using gravity	?	Relevant difference in height necessary
Wind and solar energy	?	Dependent on the location

Obviously, options for hydro generation are limited in the Netherlands. In many European areas with altitude differences though, installing micro-hydro technologies in the larger pipes of water distribution systems can convert energy from the pressure and flow into electricity (Carravetta et al, 2012).

2.5 Best practices

This section presents some of the best practices collected within the framework of the effort of the Global Water Research Coalition to devise a global Compendium "Best practices in the energy efficient design and operation of water industry assets" (UKWIR and GWRC, 2010). Next to an overview of case studies and examples of energy saving projects, the compendium presents factsheets and technical guidance on the subject areas with greatest potential.

The case studies show significant energy savings in all parts of the water cycle. Energy gains result from operational optimisation and technology improvements. Examples with potential include the improved operational set up of pumping design, on line aeration control, and energy efficient bubble aerators and sludge belt thickeners. Next to optimising energy efficiency across the water cycle, the case studies show also opportunities for energy generation. Appealing practices include biogas production from sludge (co)digestion and hydraulic energy generation from micro-turbines. Some of the best practices (UKWIR and GWRC, 2010; Frijns et al, 2012):

Operational energy optimisation: Several case studies show that substantial energy efficiency gains can be achieved by operational optimisation measures. For example, at water production site Andijk (Netherlands), the energy consumption of UV-treatment was reduced from 0.6 to 0.38 kWh/m^3 by decreasing the dissolved organic carbon level. This was achieved by changing the pH-correction after coagulation. The energy gain of this enhanced coagulation before the UV/H2O2-treatment is about 35%. This resembles a total energy gain of 7.7 million kWh/yr.

In wastewater treatment, aeration typically consumes 60% of the energy budget, and optimisation of aeration is thus key. Simple gains of up to 20% are possible on some aerobic wastewater systems by aligning control parameters with the discharge consent. At the Avedore biological wastewater treatment plant in Denmark, installation of advanced online process control (based on measurement of ammonia, nitrate and oxygen) resulted in a 16% decreased energy consumption. Its specific energy use is now reduced to 0.28 kWh/m3. Moreover, reduced mixing in the aeration tanks by 50% resulted in an estimated electricity saving of 0.75 GWh/year (Sharma et al, 2011).

Adoption of energy efficient technology: Case studies in the drinking water production and distribution, wastewater treatment and sludge treatment show the adoption of energy efficient technology. Substantial gains have been achieved with energy efficient pumps, plate aerators and belt thickening.

Pumps and pumping represent an area with large potential for energy savings. Simple gains are possible in some pumping situations where the operational set up has been changed from the design condition. Together with applying variable frequency drives and adopting energy-efficient pumps, gains of between 5% and 30% have been realised in drinking water extraction and distribution at case studies in Belgium and Germany.

Energy generation: There is high potential of energy recovery and generation from wastewater through chemical energy generation (biogas from organic carbon) and thermal energy recovery (from heat in wastewater). The recovery of chemical energy in wastewater can be maximised by organic carbon concentration for anaerobic conversion to biogas. At several WWTPs in the Netherlands the increase in primary sludge production reduces the load on aeration blowers and increases digester biogas production. The net energy efficiency is increased with sludge digestion and on site Combined Heat and Power.

The large-scale municipal WWTP of Strass, Austria, already shows that energy self-sufficiency is a feasible concept for wastewater treatment, by: maximum transfer of organics to digesters, intermittent aeration controlled by on-line effluent ammonia, high electricity efficiency from cogeneration, and energy savings from side-stream treatment (Wett et al, 2007; Nowak et al, 2011).

Also co-digestion with external organic waste increases the energy generation. Integration of a waste processing unit (food & beverages wastes, restaurants, supermarkets, slaughterhouses, milk industry) and a thermophilic co-digester on the WWTP of Budapest, which already was equipped with a sludge mesophilic digester, resulted in 10 million kWh/year electricity savings. The WWTP is now heat self-sufficient and produces 70% of its power needs. Co-digestion of sludge from grease skimming tanks at the wastewater treatment plant Grevesmühlen in Germany achieved a 4-times increased gas yield, resulting in on-site energy generation in gas engines of 113% of the electricity consumed for plant operation (Schwarzenbeck et al, 2008)

Case studies from France show the potential of hydraulic energy recovery from micro-turbines: 4.5 respectively 6 million kWh per year from a drinking water and WWTP effluent site (UKWIR and GWRC, 2010). McNabola et al (2013) show that significant potential exists for energy recovery through the use of micro-hydropower installations in water infrastructures in Ireland, however they notice that complexities such as variations in flows and turbine efficiency should be considered.

Box 2.2 Energy measures at Hamburg Wasser

Hamburg Wasser has undertaken substantial efforts towards a self-sufficient energy supply of its Köhlbrandhoft/Dradenau WWTP (Laurich, 2011). This largest WWTP of Germany (3 million p.e.) treats on average 400,000 m^3/day. The total power consumption was 98 million kWh/year. About 60% of the energy is self-produced in the sludge incineration plant. The following measures were taken to reduce the power consumption as well as to increase the energy production so that the WWTP's energy balance should be levelled by the end of 2011:

1. Installing bubble aeration in the biological stage

2. Building and operation of a wind turbine on the premise of the WWTP

3. Refining of digester gas to green gas (biomethane)

By the presented efforts about 18 million kWh/year will be saved and in total 23 million kWh/year will be produced additionally.

Another major achievement of Hamburg Wasser is the introduction of thermal energy recovery from the sewer system. In total, 215 houses are heated with thermal energy from heat exchangers in sewer in Hamburg, avoiding 700 t CO_2-eq/year.

Figure 2.6. Biogas production at WWTP of Hamburg Wasser

2.6 Conclusion

This chapter showed that large potentials exist in energy saving and generation in the water system. Examples are available of technology implementation at the water industry. It is also concluded that new concepts and technology improvements are needed that view water as a carrier of thermal and organic energy.

Although this report focuses on the technological aspects of energy saving and generation in the water system, in this final part emphasis is put on the opportunities that exist for the water sector in relation to other developments in cities. In fact, collaboration with other sectors will be essential to achieve an energy neutral urban water cycle (Frijns et al, 2013b).

As most of the energy use in the urban water cycle comes from heating water by households, it is apparent that the participation of inhabitants and the housing sector is required. Water conservation measures at households, both through water saving devices (e.g. for washing machines) and behavioural changes (e.g. less water gardening) can have a substantial contribution to a reduced amount of water to be produced and treated and thus the energy use related. This is in particular true for warm water conservation. It is thus important to address this issue with the construction and installation sector. Fortunately, in their efforts to lower the Energy Performance Coefficient of new houses, the Dutch building sector is already moving towards the implementation of warm water conservation (Nederlof and Frijns 2010). Examples of energy reduction in buildings and offices are the introduction of more efficient appliances such as better water heaters, and heat recovery from used water or extracted from the groundwater.

In fact, in the efforts of other sectors, such as building, energy, and urban planning, to become energy neutral, a large potential exist to incorporate energy efficient water initiatives as well. One can anticipate that the driving forces for change are stronger in these urban sectors than in the water sector itself. Collaboration of the water boards through the contribution of water measures as part of the carbon neutral effort of cities could well be a successful strategy. There is a clear opportunity for the water sector to incorporate water-related energy use in sustainability transformations of other sectors, e.g. in urban renewal. Novotny (2010) emphasizes the substantial contribution water conservation can have in minimizing the carbon footprint of cities.

Future city planners have to consider water, energy and nutrient flows together rather than separately and will have to design with flexibility for future changes. These flows interact, therefore the water sector should interact with other sectors to discuss common challenges and develop shared solutions. For example, Kenway et al (2011b) note the opportunities for co-managing water and energy in cities through their temporal variations. Involvement of both sectors simultaneously may help identify interdependencies as well as help address peak load issues (e.g. making use of biogas or hydropower energy produced by the water sector) which are critical to both sectors.

Indeed, a proper institutional arrangement, exemplifying the role of all involved public and private actors, will be required to better manage both water and energy sources in urban areas. Scott et al. (2011) advocate that regulatory cooperation, across sectors and jurisdictional levels for the management of resources, is needed to prevent negative trade-offs in the water-energy nexus. Unfortunately, a lack of policy integration seems to be at the heart of the problem, as is the case in many cross-sectoral issues (Hussey & Pittock, 2012).

As such, the efforts to improve the energy efficiency of the water sector and integrate water and energy in urban areas, contributes to the overall objective of TRUST towards sustainable urban water systems.

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3. IMPROVING ENERGY EFFICIENCY IN THE ALGARVE MULTI-MUNICIPAL WATER SUPPLY SYSTEM

3.1 The Algarve multi-municipal water supply system

This chapter presents the energy-efficiency measures identified for multi-municipal water supply system for the Algarve region. Energy efficiency metrics based on a whole system energy audit are presented and applied to the Algarve's Beliche system. Main results, conclusions and future developments are also presented.

The Algarve region is the southernmost region of Portugal and is the most popular touristic destination in the country receiving a high influx of visitors. It has a surface about 4,497 km^2 with approximately 450,000 permanent inhabitants (INE, 2011) in 16 municipalities (Albufeira, Alcoutim, Aljezur, Castro Marim, Faro, Lagoa, Lagos, Loulé, Monchique, Olhão, Portimão, São Brás de Alportel, Silves, Tavira, Vila do Bispo and Vila Real de Santo António). Algarve region is usually subdivided in two parts: the Westbound that is the oriental part of the Algarve and the Eastbound being the occidental part.

The water utility Águas do Algarve (AdA) was founded in the year of 2000 by a fusion between two other companies, Águas do Barlavento (westbound) and Águas do Sotavento (eastbound). AdA is a business unit of the Águas de Portugal Group – SGPS, S.A. and operates on a concessionary basis. The concession is of the Multi-Municipal Water Supply System (MMWSS) and the Multi-Municipal Waste Water System (MMWWS) for the Algarve region and for a period of thirty years long. The grantor of this company is the Portuguese State.

The MMWSS supplies about 450,000 inhabitants from October to May and almost triples during the peak of holiday season in the summer in which the estimated population is about 1,500,000 inhabitants (AdA, 2008). The whole system has four water treatment plants (WTP), 17 reservoirs, 74 municipal reservoirs, 15 chlorination points, 29 pumping stations (PS) and about 510 km of pipes with diameter varying from 60 to 1,500 mm. The pipe materials are predominantly ductile iron and high density polyethylene.

MMWSS has four water sources: Odeleite/Beliche dam that delivers raw water to Tavira and Beliche WTP; Bravura dam that supplies Fontaínhas WTP; and Odelouca dam that delivers raw water to Alcantarilha WTP since 2012/2013.

Operationally, the system is divided in two subsystems: the westbound and the eastbound. The westbound subsystem has the command centre located at Alcantarilha WTP and the eastbound subsystem has the command centre at Tavira WTP. At the boundary between the westbound and eastbound subsystems is installed a reversible pumping station (PS) that allows to transport water from one side to another inverting its direction whenever needed. This PS has several pumps as shown in Figure 3.1. These pumps have velocity variators since the water needed in each of the two directions is very different.

Figure 3.1 Reversible pumping station

3.2 Energy-efficiency measures in Águas do Algarve

3.2.1 General description

Climate Change is one of the concerns of AdA and under this theme the strategic objective of reducing emission of CO_2 into the atmosphere was defined. Additionally, one of the most important sustainability indicators for the utility stakeholders is energy consumption (AdA, 2008). Therefore, AdA has been implementing several energy-efficiency measures to achieve the goal of energy consumption reduction and increase the use of green energy, namely:

- Installation of **micro-turbines** in sites with high pressure head in excess (e.g., at the location of flow control valves or pressure reducing valves). Currently one micro-turbine is installed at the intake of Beliche Water Treatment Plant;
- Installation of **wind farms** in estates of AdA with potential for energy production;
- Installation of **solar photovoltaic systems** for energy production in outdoors of pumping stations and treatment plants or on the roof of storage tanks. Presently, AdA has installed 55 photovoltaic micro-plants and two photovoltaic mini-plants (93 kW) for energy production to sale to the public electricity network;
- Energy production through **anaerobic digestion** plants using biogas in wastewater treatment plants (WWTP). Recently, an anaerobic digestion plant using biogas was put into operation in the Lagos WWTP. It is expected an annual energy production of 250 MWh corresponding to 21 % of the electricity consumption of Lagos WWTP;
- **Scheduling electric equipment** (e.g., pumps and water treatment plants filters cleaning) **operation** during off-peak load periods which have a lower tariff rate, thereby, reducing the variable component of the electricity cost;
- Installation of **speed variators or frequency converters** in pumps;

- Improvement of **interior coating** in pump parts to increase efficiency;

- **Replacement of existing equipment** (pumps, electric motors or power converters) with high power installed by other with higher efficiency level;

- **Replacement of existing fluorescent lighting equipment** (lamps) inside the buildings by other based on LED (light - emitting diode) technology and in the outdoor by lighting flux variators.

3.2.2 Improving pump efficiency

Águas do Algarve is currently implementing energy savings measures in pumped systems, which include three main aspects:

1. Coating internal pump parts with specific paints to increase hydraulic efficiency;
2. Installing speed variators or frequency converters in pumps to allow a better adjustment of the point with higher efficiency;
3. Scheduling pumps working hours to avoid peak load periods

The pumping station of São Braz de Alportel was chosen as a pilot case study to implement these measures. This pumping station has 4 pumps, two with fixed velocity and two others with velocity variators, with one of the pump acting as a reserve. Power of each pump is 110 kW, with a flow capacity of 30 l/s. The maximum flow elevated by the pumping station is 90 l/s for a total head of 234 m. Annual energy consumption in 2012 was 1,7 GWh for a total volume of water elevated of 1,2 Mm^3.

Coating of pump's interior parts was performed in order to:

- Reduce friction in the set volute/impeller, to increase hydraulic efficiency and increase the maximum flow of the equipment;
- Reduce energy consumption
- Reduce pump wear, minimizing future maintenance needs

The chosen material for the coating was metaline (elastomeric) and belzona (metal-ceramic) with an expected efficiency gain of, respectively, 3 and 7%. Metaline was used to prevent abrasion and provide chemical protection, and belzona was used to protect the equipment from corrosion and to reduce friction.

The recovered hydraulic efficiency was around 25% and an increase of 10% when compared with the initial value was also observed. This increase leads to a 20% reduction in terms of the specific consumption, being the savings 10% higher than the value with the equipment still new. Figure 3.2 shows some examples of the coating process, before and after the procedure.

a) before coating b) after coating

Figure 3.2:Coating of pump's interior parts

The analysis of the point with higher efficiency was also conducted for pumps with variable speed. Tests were performed in order to identify the operation set points with the highest speed and lowest specific cost (€/m^3). Figure 3.3 presents the relation between specific energy costs and the velocity of the pump, where the optimal operating points were identified. In face of these results a new pump schedule was defined, reducing the energy consumption and consequently the total costs of the treatment.

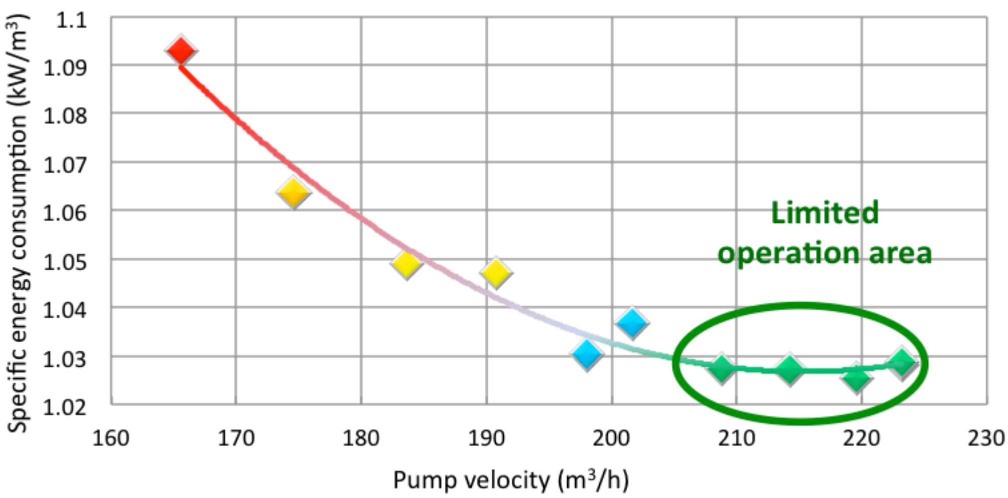

Figure 3.3 Specific energy consumption as a function of pump velocity.

The use of a remote management control system helped to minimize the reaction time to a problem, and to predict and control the system response, and therefor reduce total energy costs. In the automatic mode of the program we can see the reservoir capacity at the present instant, the potential filling/emptying level at different times, the security minimum level, the ability to level replacement as a function of the maximum flow rate of the pumping station) and even the history of consumption of the last 8 days. With all this information a better and more efficient control of the system was achieved and consequently a reduction in maintenance and energy costs.

The new pumping schedule allowed a significant reduction in energy consumption during peak hours, from 2,3% to 0,7%, and energy consumption during full hours was reduced from 44,9% to 39,3%.

The combined application of a new coating in the pumps and the new pumping schedule resulted in a reduction of 14,9% in the total energy consumption of the pumping station and a reduction of 20,3% of the total energy costs (less 19 271€ in only 8 months).

It is also important to notice that the costs of coating the pump parts were 8 600€, which had a return period of only 4 months.

3.3 Energy auditing

3.3.1 General description

The aim of an energy audit is to evaluate how much energy is consumed and to identify measures that can be undertaken to reduce consumption, to use energy more efficiently or to produce energy. Performing energy audits in water supply systems is, therefore, a crucial step to improve its energy efficiency.

Energy audits can focus only on a single electrical asset of the system (e.g., a pump) or a set of assets (e.g., a WTP), however, it can also assess the hydraulic energy consumption throughout the whole system. As such, energy audit can be divided into two main types (Souza *et al*., 2011a,b):

- **Energy audit of system electric assets** – the object of analysis is an individual asset or a set of assets with electrical energy consumption or associated to renewable sources of energy. This type of the audit is often already carried out by water utilities.
- **Energy audit of the whole system** – in this case, the object of analysis is the whole pipe system from the intake to the delivery point and assesses how much the system diverges from the ideal layout associated to the principle of the minimum energy; it is based on the time integration of the energy equation over a certain period of time.

The first type of energy auditing is already carried out by AdA and the energy-efficiency measures undertaken were included in the list of section 3.2.1. In what concerns the second type of energy auditing, it is carried out herein.

Cabrera *et al.* (2010) have proposed an energy audit based on the time integration of energy conservation equation applied to a known and controlled volume of water. This energy balance shows that the provided energy (by reservoirs and/or pumps) to the system is equivalent to the energy delivered to the users and the outgoing energy through leaks plus dissipated energy due the friction losses.

Souza *et al.* (2011) have proposed a novel standardized energy balance for water supply systems as shown in Table 3.1

Table 3.1. Energy balance (kWh/m3)

<table>
<tr><td rowspan="3">NATURAL INPUT ENERGY (E_N)</td><td rowspan="6">TOTAL ENERGY INPUT (E_E)</td><td rowspan="4">Energy dissipated-recovered (E_D)</td><td>Friction dissipated energy (E_P)</td></tr>
<tr><td>Outgoing energy through leaks – real Losses (E_L)</td></tr>
<tr><td>Local head losses in valves (E_V)</td></tr>
<tr><td rowspan="3">SHAFT INPUT ENERGY (E_B)</td><td>Recovered energy (E_T)</td></tr>
<tr><td rowspan="2">Energy delivered to users (E_U)</td><td>Minimum energy required (E_{min})</td></tr>
<tr><td>Surplus energy (E_S)</td></tr>
</table>

In the following sections each of these energy balance terms are presented.

Natural input energy

The natural input energy is the elevation energy provided by reservoirs water level (Pardo *et al.*, 2011):

$$E_N\left(t_p\right)=\gamma\cdot\sum_{i}^{N_N}\left(\sum_{k}Q_N^i\left(t_k\right)\cdot \mathrm{H}_N^i\left(t_k\right)\right)\Delta t$$

In which γ is the specific weight of water, $Q_N^i\left(t_k\right)$ and $\mathrm{H}_N^i\left(t_k\right)$ are, respectively, the flow rate supplied from reservoir i (being N_N the total number of reservoirs) and its piezometric head at time t_k. Since the analysis in extended time corresponds to a given time period $t_p=k\cdot\Delta t$, the k time intervals Δt of the analysis must be added to totalise this period.

Shaft input energy

The pumping-head provided by the pumps is:

$$E_s(t_p)=\gamma\cdot\sum_i^{N_S}\left(\sum_k Q_S^i(t_k)\cdot H_S^i(t_k)\right)\Delta t$$

where $Q_S^i(t_k)$ and $H_S^i(t_k)$ are respectively the flow rate raised by the pumping station and the pump head at time t_K.This calculation needs to be done for the N_S pumping stations that provide shaft work to the system at the k different time instants.

Balance energy dissipated-recovered

The energy dissipated is the sum of friction dissipated energy $E_P(t_p)$, the local head losses in valves $E_V(t_p)$, the outgoing energy through leaks $E_L(t_p)$ minus the recovered energy $E_T(t_p)$:

$$E_D(t_p)=E_P(t_p)+E_V(t_p)+E_L(t_p)-E_T(t_p)$$

The energy dissipated due to friction in pipes is:

$$E_P(t_p)=\gamma\cdot\sum_i^{N_P}\left(\sum_k q_p^i(t_k)\cdot\Delta H_p^i(t_k)\right)\Delta t$$

N_P is the number of pipes, $\Delta H_p^i(t_k)$ are the friction losses in pipe i at time t_k, $q_p^i(t_k)$ is the total flow rate in pipe i. The local head losses may be added to this term by calculating their equivalent piping length.

The energy dissipated due local head losses in valves is:

$$E_V(t_p)=\gamma\cdot\sum_i^{N_V}\left(\sum_k q_V^i(t_k)\cdot\Delta H_V^i(t_k)\right)\Delta t$$

Where N_V is the number of valves, $\Delta H_V^i(t_k)$ and $q_V^i(t_k)$ are, respectively, friction losses and flow rate in valve i at time t_k.

The outgoing energy through leaks is:

$$E_L(t_p)=\gamma\cdot\sum_i^{N_L}\left(\sum_k q_L^i(t_k)\cdot\Delta H_L^i(t_k)\right)\Delta t$$

In which N_L is the number of leaking nodes, $q_L^i(t_k)$ is the flow rate of leaks in the adjacent pipes to node i at time t_k, while $\Delta H_L^i(t_k)$ is the piezometric head at time t_p in the node where the leak $q_L^i(t_k)$ has been concentrated.

In situations in which there is energy recovered through the installation of micro-turbines, the recovered energy is:

$$E_T(t_p) = \gamma \cdot \sum_i^{N_T} \left(\sum_k q_T^i(t_P) \cdot H_T^i(t_P) \right) \Delta t$$

Where N_T number of nodes with turbines installed, $q_T^i(t_k)$ is the turbinated flow rate at node i at time t_k, $H_T^i(t_k)$ is the recovered head at node i and at time t_k.

Energy delivered to the users

The energy delivered to the users results from the sum of the minimum energy required to deliver water to the users $E_{\min}(t_p)$ and the surplus energy that reaches the delivered point of the users $E_S(t_p)$:

$$E_U(t_p) = E_{\min}(t_p) + E_S(t_p)$$

The minimum energy to deliver water to the users at time t_p is:

$$E_{\min}(t_p) = \gamma \cdot \sum_i^{N_N} \left(\sum_k q_N^i(t_k) \cdot H_{\min}^i(t_k) \right) \Delta t$$

in which N_N is the number of consumption nodes or delivery points, $q_N^i(t_k)$ is the flow rate delivered to users at node i at time t_k, while $H_{\min}^i(t_k)$ is the minimum piezometric head at time t_k in the consumption node i at time t_k.

Finally, surplus energy is:

$$E_S(t_p) = \gamma \cdot \sum_i^{N_N} \left(\sum_k q_N^i(t_k) \cdot H^i(t_k) \right) \Delta t$$

Where N_N is the number of consumption nodes or delivery points, $q_N^i(t_k)$ is the flow rate delivered to users at node i at time t_k, while $H^i(t_k)$ is the total piezometric head at time t_k in the consumption node I at time t_k.

3.3.2 Energy efficiency metrics

Context and performance indicators can be calculated using the results of energy auditing (e.g., dissipated energy, surplus energy), in order to assess the energy performance from different points of view (e.g., cost, energy use, water use). Several metrics have been selected for assessing energy efficiency. These are associated to performance and cost, namely:

- E1 - Energy in excess per unit of input volume (kWh/m^3);
- E2 - Energy in excess per unit of the revenue water (kWh/m^3);
- E3 - Ratio of the maximum energy in excess (-);
- E4 - Ratio of the available energy in excess (-);
- greenhouse gases produced from energy use (kgCO_2eq/m^3);
- energy production profits (€/m^3);
- consequence of a failure in Tavira's WTP (%).

For a better understanding of the proposed indexes, and since nodal consumptions vary with time the concepts will be explained in terms of energy per unit time (*i.e.,* hydraulic power). There are different types of hydraulic powers in a water supply system as presented and described in Table 3.2 and in Figure 3.4 (Duarte et al., 2008, 2009).

The higher the difference in elevation between demand nodes, the higher the value P_{min} is. When subtracting to the provided hydraulic power, the component that refers to the elevation, P_{min}, the resulting parameter allows for the comparison between different systems. Additionally, the hydraulic power in excess, P_{exc}, has the advantage of being independent of the zero-reference elevation. Since flow is time-dependent, the energy corresponding to the above referred hydraulic powers can be obtained by their time-integration for a given period of analysis.

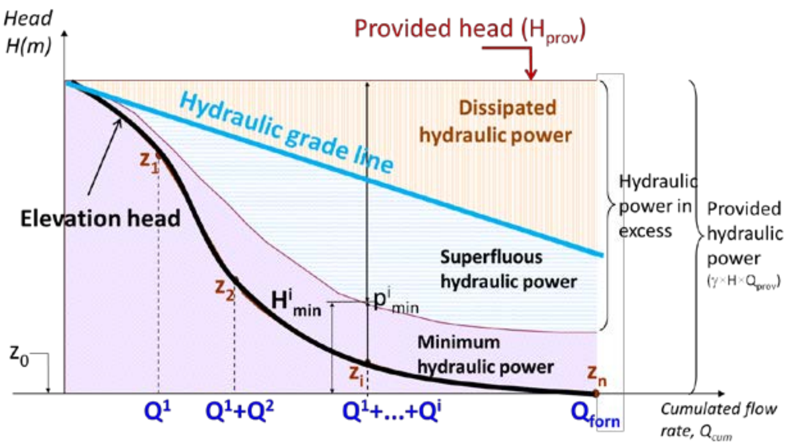

Figure 3.4. Schematic representation of the provided power, dissipated power and minimum power.

Table 3.2. Different types of hydraulic power in a water supply system

TYPE	FORMULA
Hydraulic power (in general)	$P = \gamma \cdot Q \cdot H$ in which P = hydraulic power (W); γ = specific weight (9800 Nm^{-3}); Q = flow rate (m^3/s); H = hydraulic head expressed in terms of the zero-reference level (m).
Minimum hydraulic power	$P_{min}(t) = \sum_{i=1}^{n} P^i_{min}(t) = \gamma \sum_{i=1}^{n} \left[Q^i(t) \cdot H^i_{min} \right]$ in which $P^i_{min}(t)$ = minimum hydraulic power at node *i* and at time *t* (W); $Q^i(t)$ = consumption at node *i* and at time *t* (m^3/s); H^i_{min} = minimum required head at node *i* (m); n = number of consumption nodes.
Provided hydraulic power	$P_{prov}(t) = \sum_{i=1}^{n} P^i_{prov}(t) = \gamma \cdot \sum_{i=1}^{n} \left[Q^i(t) \cdot H^i_{prov} \right]$ in which $P^i_{proc}(t)$ = provided hydraulic power at node *i* and at time *t* (W) related to initial storage tank level or pumping stations; $Q^i(t)$ = flowrate at node *i* and at time *t* (m^3/s); H^i_{min} = minimum required head at node *i* (m); n = summation of the number of water sources and the number of pumping stations.
Recovered hydraulic power	$P_{rec}(t) = \sum_{k=1}^{N_T} P^k_{rec}(t) = \gamma \sum_{k=1}^{N_T} \left[Q^k(t) \cdot H^k_{rec}(t) \right]$ where $P^k_{rec}(t)$ = recovered power at node *k* at time t; $Q^k(t)$=turbinated flow at node *k* at time *t* (m^3/s); $H^k_{rec}(t)$ = recovered head at node *k* and at time *t* (m); N_T = number of nodes with turbines installed
Hydraulic power in excess	$P_{exc}(t) = \left[P_{prov}(t) - P_{rec}(t) - P_{min}(t) \right]$

Energy in excess per unit of input volume

This index represents the theoretical potential of energy reduction per m^3 of the provided or supplied volume, V_{prov}. It should be as low as possible, though it is always a positive value. It is an adequate index to assess the impact of different energy management measures; however, it does not allow for the assessment of the impact of leakage control measures in energy efficiency. For this reason, E1 is not adequate for the comparison of systems with different water losses levels.

$$E1 = \frac{E_{exc}}{V_{prov}} = \frac{\int P_{exc}(t)dt}{\int Q_{prov}(t)dt}$$

Energy in excess per unit of the revenue water

This index represents the theoretical potential of energy reduction per m^3 of revenue water. Similarly to the previous index, E2 is always a positive non-zero value, ideally as low as possible. The aim of using the revenue water (Q_{rev}) in denominator (instead of the input flow) is to allow the index to reflect the impact of leakage control measures in terms of energy. If real losses are improved, the index will have a lower (better) value, since the numerator diminishes (Q_{prov} is lower) and the denominator is the same. Therefore, E2 has advantages in comparison with E1 and should be preferred. Interventions that result in the improvement of the dissipated energy (*e.g.*, pipe rehabilitation) will only be reflected in indices E1 and E2 if changes result into reduction of the total provided head at the source (*i.e.,* provided hydraulic power). Measures that lead to the reduction of apparent losses are most of the times associated to an increase of the revenue water and will have a direct effect in the reduction of index E2, not only because the denominator increases but also because the numerator diminishes (i.e., provided power is the same, but the minimum power increases).

$$E2 = \frac{E_{exc}}{V_{rev}} = \frac{\int P_{exc}(t)dt}{\int Q_{rev}(t)dt}$$

Ratio of the energy in excess

This index quantifies, in a straightforward way, the theoretic energy in excess that is provided to the system. Similarly to the previous two indices, the provided hydraulic head includes the head losses component, reason why it is always superior to 1. It has the disadvantage of depending of the zero-reference elevation.

$$E3 = \frac{E_{prov} - E_{rec}}{E_{\min}} = \frac{\int (P_{prov} - P_{rec})(t)dt}{\int P_{\min}(t)dt}$$

Ratio of the available energy in excess

This index quantifies, in a straightforward way, the effective energy in excess that is provided to the system. Unlike the previous indices, it does not include the head losses component, being more realistic than E3 of the potential energy available for recovery in comparison with the minimum required.

$$E4 = \frac{E_{prov} - E_{rec} - E_{headlosses}}{E_{\min}} = \frac{\int (P_{prov} - P_{rec} - P_{headlosses})(t)dt}{\int P_{\min}(t)dt}$$

Greenhouse gases (GHG) produced from energy use

This metric intends to determine how much greenhouse gas (GHG) emissions can be reduced by producing electricity through the use of micro-turbines installed in water supply systems and can be determined by:

$$E5 = f_{GHG}(E_S - E_{rec})$$

Where E5 is GHG produced from energy use (kg CO2eq/m^3); f_{GHG} is a conversion factor (kg CO2eq/kWh); ES is shaft input energy from the pumps (kWh) and E_{rec} is recovered energy produced by turbines (kWh).The f_{GHG} estimated by the Portuguese electricity company is of 0.427 kg CO2eq/kWh.

Energy production profits

Energy production profits (E6) measures the benefit to the water utility by reducing the electric energy purchased from national electric company by consuming the energy produced in the micro-hydro power plant installed in Beliche's WTP. It could be assessed as a ratio between the input shaft energy (E_S) and the recovered energy (E_{rec}):

$$E6 = \frac{E_{rec}}{E_S}$$

Consequence of a failure in Tavira's WTP

This metric intends to measure the impact to the users if a failure that forces the stoppage of Tavira's WTP during an interruption period. This should be a risk metric but since the likelihood of failure due an event that forces a stoppage of a WTP is not easy to estimate, it was decided to assess using a consequence dimension. Note that Beliche system has two WTP but only Tavira's WTP is considered. The main reason is that if Beliche's WTP fails, full supply to the users is guaranteed from Tavira's WTP. This metric is a ratio between full supply and the percentage of undelivered volume:

$$E7 = 1 - \frac{V_{uns}}{V_{prov}}$$

Where E7 is the consequence of a failure in Tavra's WTP; V_{uns} is the undelivered volume (m^3) and V_{prov} is the total provided volume to the system (m^3) during the interruption period. The interruption period considered was at least one day.

3.3.3 Multi-criteria decision making methods

Type of methods

The main purpose of multi-criteria decision making (MCDM) is to provide decision aiding tools that help finding solutions for real-world problems, most often, problems having conflicting points of view.

The multi-criteria problem is related to the methods and procedures by which the different criteria can be formally involved in the decision process. Generally, these problems fall into multi-attribute (discrete problems) or multi-objective problems (continuous problems). So, Multi-Criteria Decision Analysis (MCDA) problems can be roughly divided into two main groups, viz. multiple attribute decision-making (MADM) and multiple objective decision-making (MODM) problems. In the MADM problems, the decision-maker must choose from among a finite number of available alternatives characterized by a set of multiple attributes (metrics) (Figueira *et al.*, 2005).

The methods of MADM can be divided into three main groups (Vincke, 1992; Roy, 1996): (i) methods based on the use of a single synthetizing criterion without incomparability (e.g., simple additive weighting); (ii) methods based on outranking relations with incomparability (e.g., ELECTRE); and (iii) methods based on interactive local judgments with trial-and-error iteration. While the first two groups embody a clear mathematical structure, the third does not use any formalized procedure (Getzner *et al.,* 2002).

Decision matrix

A MADM problem can be easily expressed in a matrix format. A decision matrix is a M×N matrix in which each element e_{ij} indicates the performance of alternative a_i when it is evaluate of decision criterion g_j (for j=1, 2,..., M and i=1,2,...,N). It is also assumed that the decision-maker has determined the relative importance or weights of the decision criteria (denoted as w_j for j=1, 2,.., M):

		criteria			
		g_1	g_2	...	g_M
alternatives	a_1	e_{11}	e_{12}	...	e_{1M}
	a_2	e_{21}	e_{22}	...	e_{2M}
	...	...	...	...	...
	a_N	e_{N1}	e_{N2}	...	e_{NM}
weights		w_1	w_2	...	w_M

In this report the decision criteria are also called metrics.

Simple additive weighting

The simple additive weighting (SAW) method also called as weighted sum method (WSM) is one of the best known and used methods. In this method the alternatives are ranked based on their weighted sum score (Tzeng and Huang, 2011):

$$V(a_i) = \sum w_j \cdot g_j(a_i)$$

Where: $V(a_i)$ is the ranking score for alternative a_i; w_j is the weight of criterion *j*; and $g_j(a_i)$ is the normalized preferred rating of alternative a_i with respect to criterion *j*.

For commensurable comparison all scales of the criteria need to be normalized and all scales need to have the same preference direction (minimization or maximization) depending on the problem. If the problem is of maximization a higher ranking score $V(a_i)$ means a better alternative and if the problem is of minimization a higher ranking score $V(a_i)$ means a worst alternative. For example, if all criteria represent benefits, then the most preferred alternative is the one with the largest cumulative value $V(a_i)$ (Triantaphyllou and Baig, 2005). Several types of normalization techniques can be used to normalize the scales being the most used ratio normalization.

ELECTRE III

ELECTRE (*ELimination et Choix Traduisant la RÉalité*) methods are a family of MCDA techniques developed in France. Since their development, which started in the 1960s, ELECTRE methods have been widely used in many real-world decision problems (e.g. energy, transportation, environmental and water management) and proved to be suitable for situations where at least five decision criteria are involved (Rogers and Bruen, 2000; Dias *et al.*, 2006; Figueira *et al.*, 2005).

ELECTRE family includes several methods distinguished by the type of problems involved, such as choice, ranking or sorting. The ELECTRE III method is used to rank alternatives from the best to the worst one.

To take into account the imperfect nature of the evaluation of alternatives, ELECTRE III makes use of discrimination thresholds (indifference and preference) resulting in a pseudo-criteria model of preferences (Figueira et al., 2010). To use a true-criteria model such as in SAW, the discrimination thresholds in ELECTRE III method can be considered as equal to zero.

The ELECTRE III method starts by a pairwise comparison of each alternative to the remaining one in order to accept, reject, or, more generally, assess the credibility of the assertion "alternative *a* is at least as good as alternative *b*" (Dias *et al.*, 2006).

This method involves two phases: the construction of one or several outranking relation(s) followed by an exploitation procedure. The outranking relation is built through the following steps (Dias *et al.*, 2006); Mousseau *et al.*, 1999):

(i) computation of the partial concordance indices $c_j(a,b)$ and $c_j(b,a)$:

$$c_j(a,b)=\begin{cases} g_j(a)\le g(b) & \text{then} \quad c_j(a,b)=0 \\ g_j(a)>g(b) & \text{then} \quad c_j(a,b)=1 \end{cases}$$

$$c_j(b,a)=\begin{cases} g_j(a)\ge g(b) & \text{then} \quad c_j(b,a)=0 \\ g_j(a)<g(b) & \text{then} \quad c_j(b,a)=1 \end{cases}$$

(ii) computation of the overall concordance indices $c(a,b)$ and $c(b,a)$:

$$c(a,b)=\frac{\sum w_j c_j(a,b)}{\sum w_j}$$

$$c(b,a)=\frac{\sum w_j c_j(b,a)}{\sum w_j}$$

(iii) computation of the partial discordance indices $d_j(a,b)$ and $d_j(b,a)$:

$$d_j(a,b)=\begin{cases} g_j(a)\le g(b) & \text{then} \quad d_j(a,b)=1 \\ g_j(a)>g(b) & \text{then} \quad d_j(a,b)=0 \end{cases}$$

$$d_j(b,a)=\begin{cases} g_j(a)\ge g(b) & \text{then} \quad d_j(b,a)=1 \\ g_j(a)<g(b) & \text{then} \quad d_j(b,a)=0 \end{cases}$$

(iv) computation of the fuzzy outranking relation grounded on the credibility indices $\sigma(a,b)$ and $\sigma(b,a)$:

$$\sigma(a,b)=c(a,b)\prod_{j\in \bar{F}}\frac{1-d_j(a,b)}{1-c_j(a,b)} \quad \text{where} \quad \bar{F}=\left\{ j\in F \mid d_j(a,b)>c_j(a,b)\right\}$$

$$\sigma(b,a)=c(b,a)\prod_{j\in \bar{F}}\frac{1-d_j(b,a)}{1-c_j(b,a)} \quad \text{where} \quad \bar{F}=\left\{ j\in F \mid d_j(b,a)>c_j(b,a)\right\}$$

(v) determination of a λ-cut of the fuzzy relation in order to obtain a crisp outranking relation (

(vi) Figure 3.5. Outranking relation

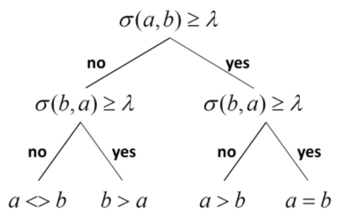

Figure 3.5. Outranking relation

The λ-cut represents the majority of criteria in favour to the assertion "alternative *a* is at least as good as alternative *b*" and therefore it should be always in the interval] 0.5; 1.0].

3.3.4 Case study

The analysed case study is a subsystem of the eastbound MMWSS for the Algarve region in Portugal: the Beliche system (Carriço et al., 2013). This system is supplied by Beliche dam and raw water is treated in both Tavira and Beliche WTP. This reservoir aims at irrigation and water consumption uses.

The system has two operating schemes due to the seasonality of tourism: one for the high season from June to September (Figure 3.6a); and the other one for the low season from October to May (Figure 3.6b). At the low season, only Tavira WTP is operating and water is conveyed from Beliche to Tavira by a raw water main with 28 km (Figure 3.6). At the high season, both Tavira and Beliche WTP's are operating and part of the water is conveyed to Beliche WTP through a 1 km long pipe (Figure 3.6).

The raw water main from Beliche to Tavira WTP has two pumping stations. At the upstream of Beliche WTP, there is a micro-hydropower plant with two pumps-as-turbine installed.

The system downstream Tavira WTP has four pumping stations, four in-line storage tanks and delivers water to 20 municipal tanks as shown in Figure 3.6. It is composed of 115 km of pipes with diameters from 40 to 1500 mm.

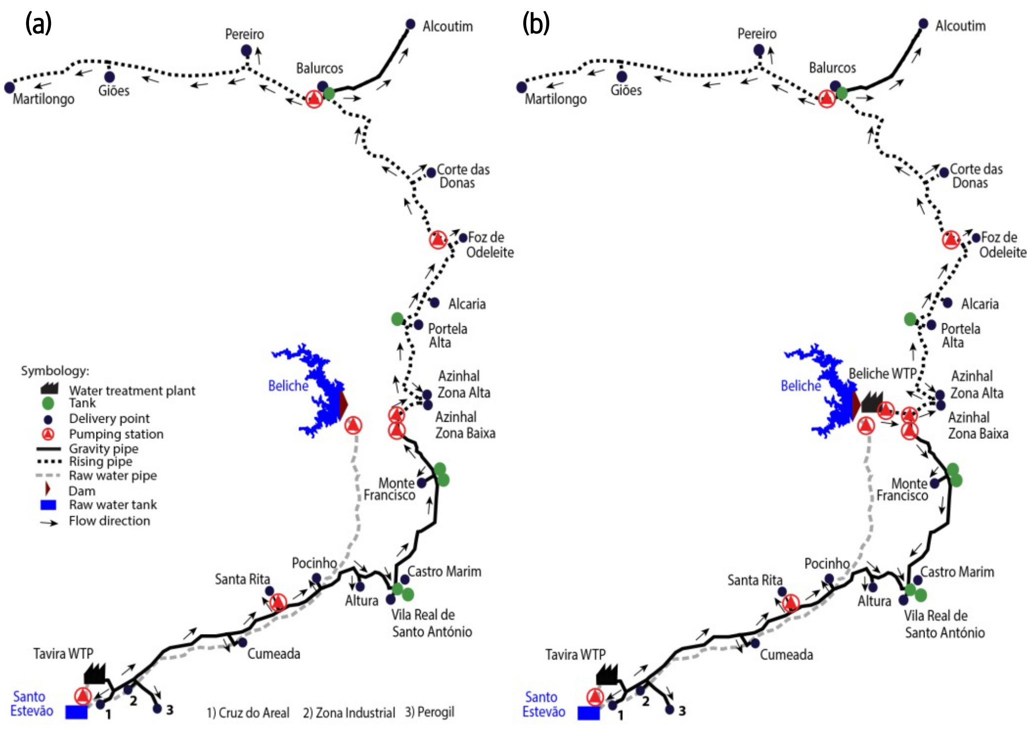

Figure 3.6. Operating schemes of the Beliche system at: (a) Winter; (b) Summer

3.3.5 Main results

The aim of this analysis is to compare the energy efficiency of the Beliche system for two operating schemes using the referred four energy metrics:

- Operation Scheme 1 (OS1) – water is treated only in the Tavira WTP; neither Beliche WTP nor the micro-hydro power plant are operating;
- Operation Scheme 2 (OS2) – 78% of water is treated at Tavira WTP and 22% is treated at Beliche WTP; the micro-hydro power plant is operating.

The hydraulic simulator EPANET was used to assist the calculation of the energy efficiency performance indices. The hydraulic model was provided by the water utility AdA. Flow rate data were collected at each delivery point during the year of 2012 and used to calculate delivery water volumes per month (Figure 3.7).

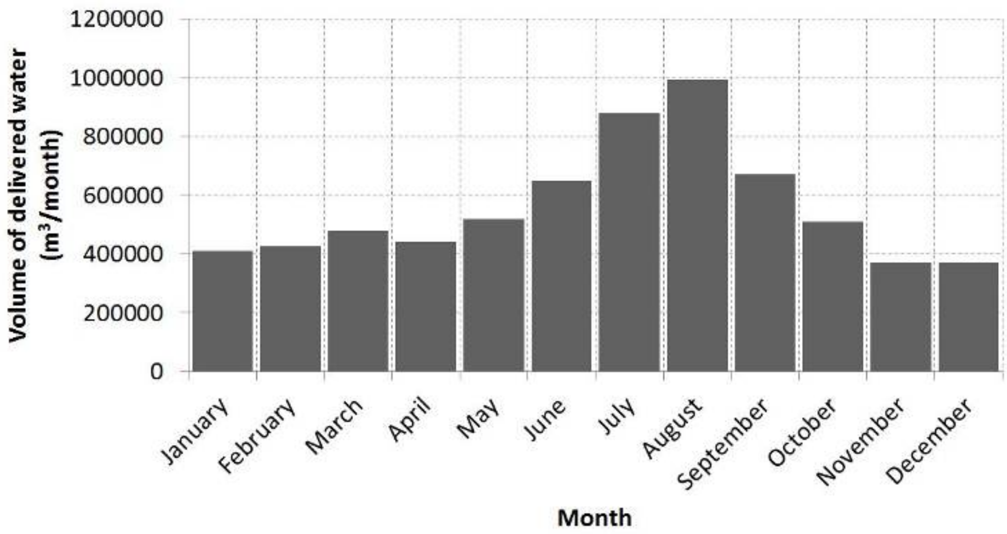

Figure 3.7. Volume of delivered water per month in 2012

Two representative months were selected: January for the low season (LS) and July for the high season (HS). This two demand scenarios were considered for each operating scheme (OS1 and OS2) to assess energy efficiency, and four situations were simulated: OS1-HS, OS2-HS, OS1-LS, OS2-LS.

The energy balance was calculated using the hydraulic model for each scenario. The dissipated energy along the system is given by the difference between the provided energy and the delivered energy at the consumption nodes. The surplus energy corresponds to the difference between the delivered energy and the minimum required energy. The dissipated and surplus energies, expressed in terms of head, for the subsystem considering the Operation Scheme 2 with the high season demand (OS2 HS) are presented in Figure 3.8. The upper bound to the area corresponds to the provided head (hydrostatic head) and the three sections at which it suddenly increases correspond to pumping stations (PS). The limit between the dissipated power and the surplus power correspond to the hydraulic grade line.

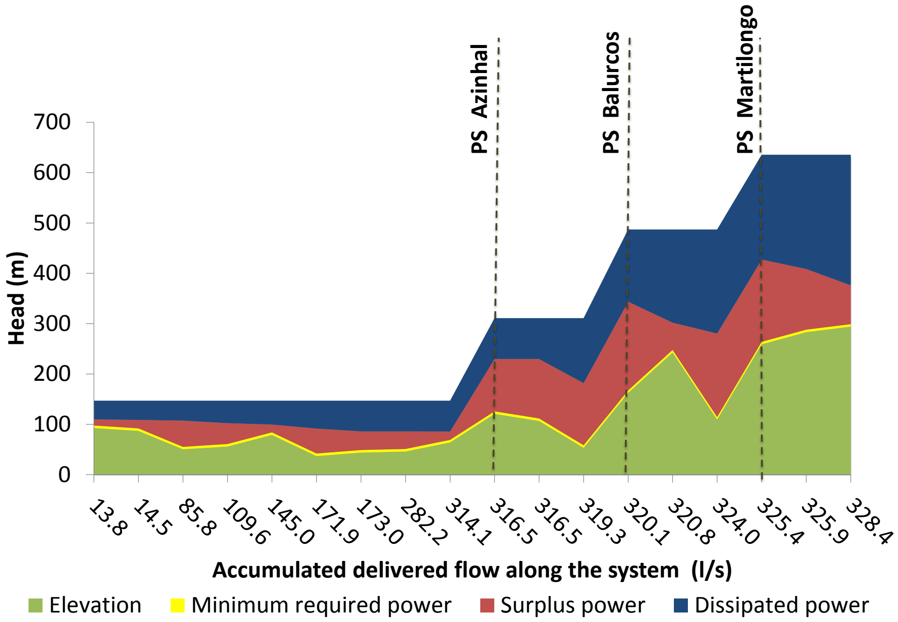

Figure 3.8. Minimum, surplus and dissipated power

To determine the total provided power, it is necessary to calculate the hydraulic power at the pumping stations as shown in Table 3.3 for the four situations.

Table 3.3. Hydraulic power of the pumping stations

PUMPING STATION	OS1-HS			OS2-HS			OS1-LS			OS2-LS		
	Q (l/s)	H (m)	P_{prov} (W)	Q (l/s)	H (m)	P_{prov} (W)	Q (l/s)	H (m)	P_{prov} (W)	Q (l/s)	H (m)	P_{prov} (W)
Santa rita	3.1	38	1,168	3.1	38	1,168	1.8	39	669	1.8	39	669
Beliche i	–	–	–	36.7	69	24,776	–	–	–	36.6	69	24,678
Beliche ii	–	–	–	36.7	69	24,776	–	–	–	36.6	69	24,678
Azinhal i	7.1	164	11,456	14.3	148	20,656	4.0	168	6,571	8.0	163	12,745
Azinhal ii	7.1	164	11,456	–	–	–	4.0	168	6,571	–	–	–
Balurcos i	9.0	176	15,614	4.5	300	13,291	6.1	267	15,863	3.0	323	9,585
Balurcos ii	–	–	–	4.5	300	13,291	–	–	–	3.0	323	9,585
Martilongo	4.4	148	6,381	4.4	148	6,381	3.3	207	6,760	3.3	207	6,760

The raw water main that conveys water from Beliche dam to Tavira WTP has two pumping stations being necessary to sum the provided hydraulic power of each to the total provided power (Table 3.4).

Table 3.4. Provided hydraulic power

RAW WATER MAIN	OS1-HS			OS2-HS			OS1-LS			OS2-LS		
	Q (L/s)	H (m)	P_{prov} (W)	Q (L/s)	H (m)	P_{prov} (W)	Q (L/s)	H (m)	P_{prov} (W)	Q (L/s)	H (m)	P_{prov} (kW)
Beliche reservoir	332.21	45	25,720	153.26	45	11,865	332.21	45	25,721	153.26	45	**11,865**
Pumping station 1	332.21	87	283,242	153.26	87	130,669	259.12	87	220,926	73.13	87	**68,319**
Pumping station 2	332.21	15	48,835	153.26	15	22,529	259.12	15	38,091	73.13	15	11,779

There is a micro-hydro power plant in Beliche, the recovered hydraulic power was calculated assuming the total flow is turbinated with a 15 m head (Table 3.6).

Table 3.5. Recovered hydraulic power of the micro-hydro power plant

MICRO-HYDRO POWER PLANT	OS1-HS			OS2-HS			OS1-LS			OS2-LS		
	Q (L/s)	H (m)	P_{rec} (W)	Q (L/s)	H (m)	P_{rec} (W)	Q (L/s)	H (m)	P_{rec} (W)	Q (L/s)	H (m)	P_{rec} (W)
Beliche	–	–	–	73,1	15	10,750	–	–	–	73,1	15	10,750

The energy efficiency performance indices obtained are presented in **¡Error! No se encuentra el origen de la referencia.** 3.9.

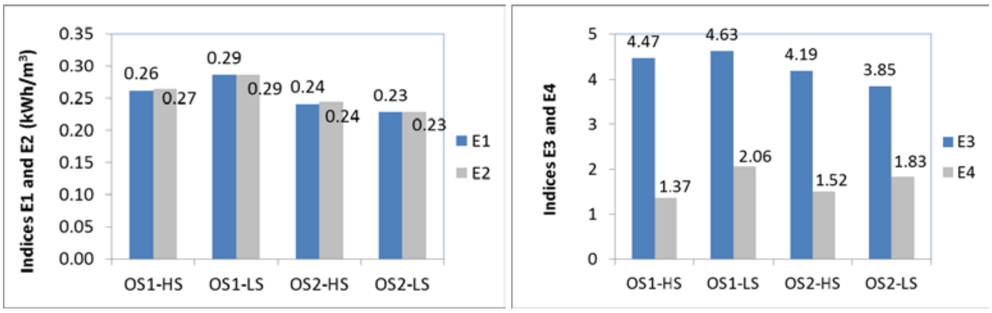

Figure 3.9: Energy efficiency performance indices

The values of indices E1 and E2 are almost the same for both operating schemes and consumption scenarios, because water losses are very small (i.e., 1-2%) and, consequently, provided water volume and revenue water volume are almost the same.

Operating scheme OS2 for both low and high season (LS, HS) has lower E1 and E2 indices (0.23-0.24 kWh/m^3) than the OS1 (0.27-0.29 kWh/m^3), meaning that it requires less energy per m^3 of delivered/provided water, having a better energy efficiency. This is because in OS2 part of the water is treated in Beliche WTP and does have to go through a longer way in the raw trunk main (with several pumping stations); additionally, there is a hydropower plant at Beliche to recover energy.

Index E3 expresses the theoretical energy in excess that is provided to the system in comparison to the minimum energy necessary (i.e., 5 m): E3 is lower in OS2 than in OS1, as the other indices pointed out. E3 values vary between 3.9 and 4.6, which means that provided energy is approximately four times the minimum energy needed. As E3 values are lower in OS2 than in OS1, the former has lower potential of energy recovery than the latter.

Index E4 expresses the potential energy available for recovery in terms of the energy minimum required (i.e., 5 m). E4 varies between 1.4 and 2.1, which means that, on average, only between 2 and 5 m of energy can be recovered by the installation of micro-turbines in the delivery points (i.e., at the entrance of the storage tanks), or the reduction in pumping head by means of the use of variable speed pumps, for example. However, these indices do not take into account the existence of high sections in the pipe profile that may not allow this energy recovery. A more detailed analysis is necessary for the assessment of whether it is worth installing the speed variators at the existing pumping stations and to identify the best points for the installation of micro-hydropower plants.

Only indexes E2 and E4 were chosen for aggregation since E1 and E3 were considered redundant metrics.

Table 3.6 presents the results obtained of the energy efficiency metrics considered for aggregation. In red are represented the worst value and in green the best value for each metric. The weights were attributed by a panel of technical specialists of the water utility considering three points of view: environmental (E1, E2 and E3), financial (E4) and social (E5).

Table 3.6. Results of the energy efficiency metrics (decision matrix)

ALTERNATIVES	E2 (kWh/m^3)	E4 (-)	E5 (kg CO_2eq)	E6 (%)	E7 (%)
OS1-HS	0.27	1.37	161.5	0	100
OS1-LS	0.29	2.06	80.9	0	100
OS2-HS	0.24	1.51	151.0	2.9	51.7
OS2-LS	0.23	1.83	67.5	6.3	47.6
Preference direction	↓	↓	↓	↑	↓
Weights	0.2	0.2	0.3	0.2	0.1

In a rough analysis based only on the number of metrics it seems that the best option is OS2-LS and the worst is OS1-LS.

To apply SAW method the decision matrix need to be normalized. If the metric preference direction is of minimization the following equation should be used:

$$e_{ij} = \frac{\max e_{ij}}{e_{ij}}$$

Otherwise next equation should be considered:

$$e_{ij} = \frac{e_{ij}}{\max e_{ij}}$$

The normalized decision matrix obtained is shown in Table 3.7.

Table 3.7. Normalized decision matrix

OPERATION SCHEME	E2	E4	E5	E6	E7
OS1-HS	1.07	1.5	1.0	0.0	1.0
OS1-LS	1.00	1.0	2.0	0.0	1.0
OS2-HS	1.21	1.4	1.1	0.5	1.9
OS2-LS	1.26	1.1	2.2	1.0	2.1
Weights	0.2	0.2	0.3	0.2	0.1

The results obtained using SAW method to rank the different alternatives, considering the normalized decision matrix in Table 3.7, are presented in Figure 3.10.

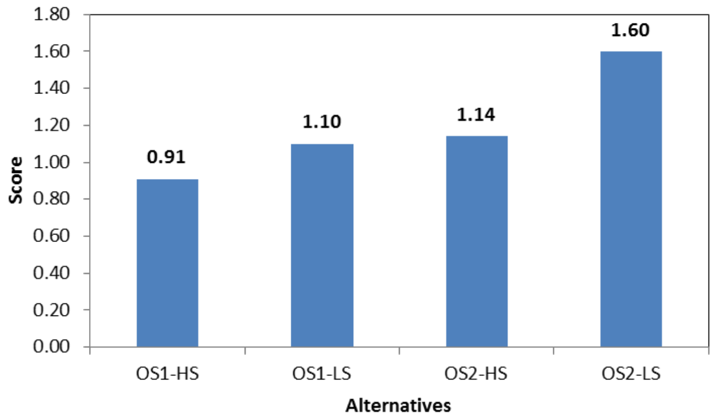

Figure 3.10. Ranking obtained with SAW method

The Decision Deck platform was used to apply the ELECTRE III method and the results obtained are shown in Figure 3.11.

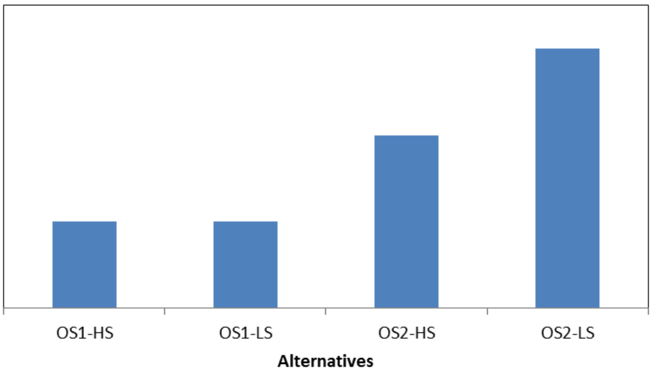

Figure 3.11: Ranking with ELECTRE III method

In both methods the best option is OS2-LS followed by OS2-HS which means that is better to have Beliche's WTP working the whole year and not only at the high season. The main difference in the results obtained with both methods is that with ELECTRE III the alternatives OS1-HS and OS1-LS are ranked ex aequo and that does not happen with SAW method.

The results are coherent since OS2-LS is better than all others options in at least four metrics (E2, E5, E6 and E7) and OS2-HS is the second better in other four metrics (E2, E4, E5 and E6).

The main drawbacks of SAW method are that adding or removing alternatives may change ranking; is difficult to use for qualitative scales and depends hardly of normalization used. The main advantage is that its simplicity allows using a normal spreadsheet to rank the alternatives.

ELECTRE III is more sophisticated than SAW method, which can use discrimination thresholds incorporating in that way the imperfect nature of the evaluations. If by one hand this is an advantage by the other is a disadvantage because assigning values to these discrimination thresholds is not a trivial task.

3.4 Summary and conclusions

The aim of this chapter consisted in identifying measures to improve energy efficiency in the Algarve multi-municipal water supply system.

Several actions taken to produce energy as well as to improve energy efficiency were presented, including a case study of the pumping station of São Bráz de Alportel.

The combined application of a new coating in the pumps and a new pumping schedule resulted in a reduction of 12,9% in the total energy consumption of the pumping station and a reduction of 20,3% of the total energy costs , with a payback period of only 4 months.

A methodology to perform an energy audit was presented, based on energy balance and four performance indices. An example of application to the Beliche system is also included in the report to illustrate the recommended methodology and demonstrate the robustness and practical interest of the proposed new performance measures. Two operating schemes have been compared: it has been shown that OS2 is the most efficient as the water is supplied using less pumping energy, whereas OS1 has the highest potential of recovery.

The applications of the two multi-criteria decision making methods have shown that the best option is OS2-LS followed by OS2-HS which means that is better to have Beliche's WTP working the whole year and not only at the high season. The main difference between the two methods lies with the last two options since ELECTRE III gives an *ex aequo* rank and SAW does not allow this. Despite this difference the methods gives coherent results.

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4. ENERGY AUDIT OF A WATER DISTRIBUTION NETWORK - ALCOY CASE STUDY

4.1 Introduction

Energy assessment of water distribution networks is a key goal for water utilities. In a permanent energy crisis scenario and being sustainable water management becoming very energy consuming, to do more with less is crucial. Just as a matter of fact, wasting significant amounts of water and energy through leaks is, simply, unacceptable. Energy is commonly lost as a result of network leakage, and such energy loss results not only from the energy leaving the system through leaks (which can be quite relevant depending on the energy footprint of the previous steps of the urban water cycle, mainly when water comes from desalination plants) but also from the extra energy needed to overcome additional friction losses created by higher flow rates in pipes. By the other hand, when possible it is important to recover the unavoidable topographic energy existing in hilly cities with an irregular profile (Cabrera et al., 2014).

The audit presented in Cabrera et al. (2010) allows to identify the final uses of the energy that enters into the system, and thus to perform an assessment that characterizes the network behaviour from an energy perspective. Context information and energy indicators summarise the energetic performance of the whole system. The energy audit can be used to evaluate the Green House Gas (GHG) impacts, which depend on the sources of water and energy (Cabrera et al., 2009). In order to have a more holistic point of view, a cost-benefit analysis including environmental costs can be performed. These new tools could easily be used from a regulatory or administrative perspective to create incentives for a more sustainable urban energy management in water distribution systems. The energy audit, and related indicators, requires a previous water audit and a mathematical calibrated model of the network. Both audits must be applied to similar boundaries (either to the whole network or a sector) as has been done in the case study, Alcoy, that follow, although in this brief summary only global results are presented. Last, it is important to explore the possibility to recover energy (Cabrera et al, 2014).

4.2 System description

The case study herein presented corresponds to Alcoy water distribution network, a coastal hilly city between Valencia and Alicante, Spain. The obtained results are very promising. Figure 4.1 depicts its lay out. The network contains approximately 182 km of pipes supplying water to a population of 50,000 inhabitants, 6000 connections (34 connections/km). The highest node of the network is 754 m over the sea level while the lowest is just 466 m. Water is supplied from three different injections points. The mathematical model has been built without simplifications (10514 nodes and 10872 pipes). All the connections have been included in a model that can be directly charged from the consumer demands files. This is very important, mainly in cities with a high variable demand along the year, as happen in the touristic coastal ones.

Complementary data of the network are:

- Eleven tanks
- Two pumping stations at the heads of the network.
- Six booster pumping stations in different points of the network.
- Fifty seven shut off valves
- Eight Pressure reducing valves
- Three - month water billed

Table 4.1. Water billed (2012)

JANUARY - MARCH	APRIL - JUNE	JULY - SEPTEMBER	OCTOBER - DECEMBER	TOTAL
735853	726123	867759	744499	3.074.234

Figure 4.1. Alcoy network layout

Leaks have been loaded as a pressure dependent demand, while apparent losses are loaded sharing the same pattern demand than users. All in all, the model reproduces very well the physical system. It is highlighted by Figure 4.2 that compares the measured flow (blue) with the model flow (red). Other flows or pressure comparisons show a similar trend.

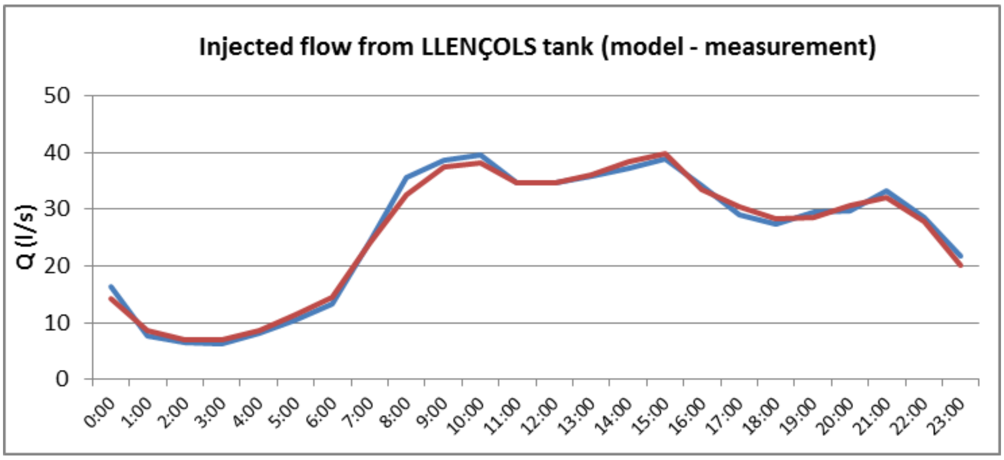

Figure 4.2: Alcoy network model versus real system

4.3 Energy Audit results

Following the methodology explained in Cabrera et al. (2010) the energy audit for the system has been performed (Table 4.2). The energy equation has been extended over a period of time of one day.

Table 4.2. Energy audit of the Alcoy network

<table>
<tr><th colspan="3">ALCOY NETWORK ENERGY AUDIT (kWh/day)</th></tr>
<tr><td rowspan="7">$E_{sr,n}$=6.015,498 kWh/day

$E_{sr,p}$=2.407,31 kWh/day</td><td rowspan="2">E_u=4.094,97 kWh/day</td><td>E_{uo}=3.482,08 kWh/day</td></tr>
<tr><td>E_{tr}+E_e=620,38 kWh/day</td></tr>
<tr><td>E_{wl}=1.587,24 kWh/day</td><td rowspan="5">$\eta_{ar} = \frac{E_{uo}}{E_{sr}} = \frac{3482,08}{8423,25} = 0,413$</td></tr>
<tr><td>E_{wf}=477,539 kWh/day</td></tr>
<tr><td>$E_{wf(valv)}$=1.526,76 kWh/day</td></tr>
<tr><td>E_{stored}=-253,071 kWh/day</td></tr>
<tr><td>E_{wp}=733,541 kWh/day</td></tr>
</table>

The main conclusions that from this audit can be obtained are:

- A great percentage of the energy supplied is gravitational (natural) because water flows from a main source located at the top of the city (6015,498 / 8422.808 = 0,71 %). This is because 2012 was a very humid year. In any case, in drought periods this percentage is substantially lower.

- Energy really delivered to users Eu (4094,97 kWh/day) is substantially higher than requested, 30 m (Euo = 3482,08 kWh/day)

- Energy embedded in the leaks (Ewl = 1587,24 kWh/day) represents 19 % of the total energy supplied. Then is a significant room for the improvement.

- Friction losses in pipes Ewl are not significant (477,539 kWh/day), because the network is oversized. Most of the pipe diameters are one or two sizes over.

- Friction losses in PRVs, Ewf are important (1526,76 kWh/day). As pressures are very high in the system it is convenient to dissipate some energy in PRVs in order to diminish water losses.

- The energy stored, Estored is negative (-253,071 kWh/day) because at the end of the day analysed, the tanks of the network have a lowest level that at the beginning of the day.

- The last term of the audit Ewp corresponds to the energy lost in pumping stations. This figure is the result of a 70% average efficiency (1 – 733,541/2407,31 = 0,695).

Although a deeper knowledge of the system is gained applying the audits to water sectors, in this summary report just global values are presented. The global efficiency of the system (Cabrera et al., 2014) is 0.413 while the theoretical one is 0,519.. The difference is a clear indicator about the global margin of improving that exists. The complementary value to this ideal efficiency (1-0,519=0,421) is the topographic energy embedded in the water network. It is very high because corresponds to a very hilly city. Although theoretically all that energy could be recovered, in real systems just a few percentage (if any) of this total can be saved with a PATs.

4.4 Main conclusions

To the light of the preceding audit, it is clear that some improvements will worth to be implemented. In synthesis these are:

- There is an appropriate spot to install a PAT (Figure 4.3). The energy that can be daily recovered is estimated in 631,2 kWh/day. It is the result of an available head of 100 m, with an average flow of 80 l/s, an energy that actually is wasted (VRP friction).

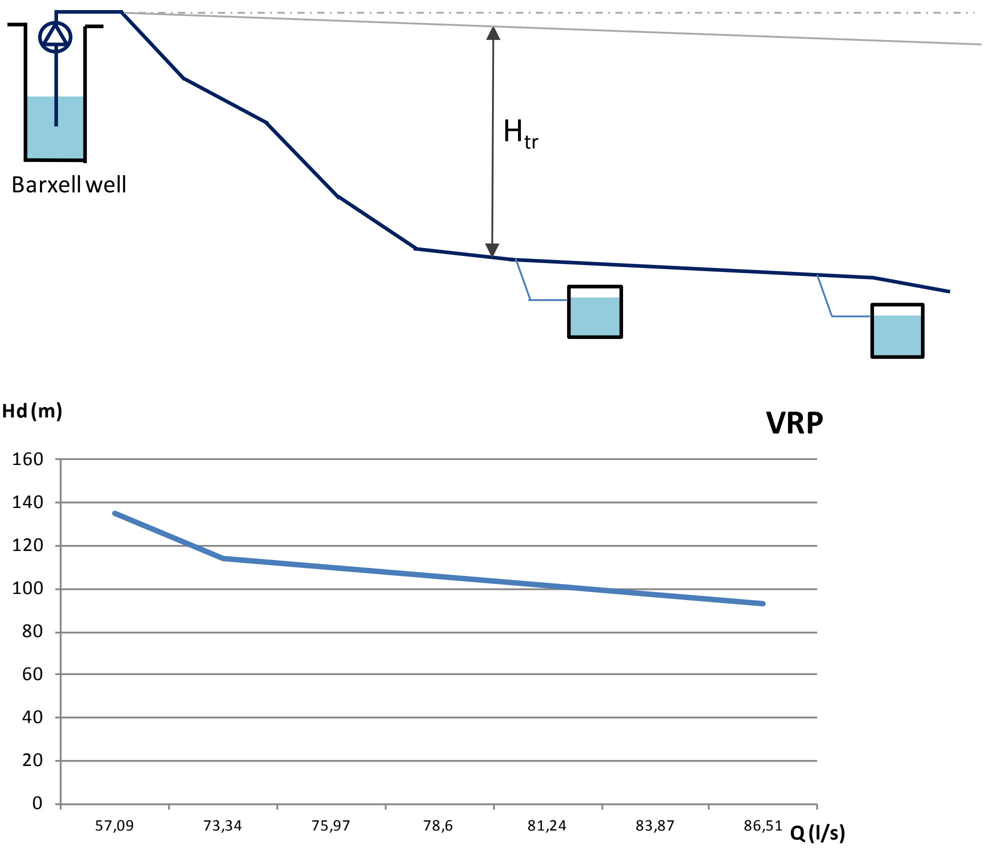

Figure 4.3. PAT to be installed in Alcoy network

- Losses should be minimized.
- Efficiencies in pumping stations should be improved.
- There are other actions that worth to be taken (i.e. to withdrawn a booster station because supplies energy that it is not strictly necessary).

In any case a final cost benefit analysis for all these actions must be performed. It is important to determine the revenue period for each one. In our case all the investments can be recovered in some few years.

Summarising, energy audits of pressurized water network, to be obtained from the integral energy equation and its integration in extended period, give a general picture of the problem. They clearly indicated where are located the best pouches saving of energy. Input energy (pumps, reservoirs) is equal to the energy consumed by users (through demanded water) plus leakage and friction energy losses in pipes. Energy audit requires the previous water audit as well as the mathematical model of the distribution network. From the energy audit, context and performance indicators (Cabrera et al., 2010) are calculated in order to assess the energy performances of the system. Furthermore, these indicators will help to identify future actions devoted to improve the network's energy efficiency. Cost-benefit analysis is required to decide the best strategy to implement in practice. An approach that can be resumed in a very well known sentence: *Think globally, act locally* and highlighted in this case study.

4.5 References

Cabrera, E., Pardo, M.A., Cobacho, R., Arregui, F.J. and Cabrera, E. Jr.(2009). "*Evaluation of Carbon Credits Saved by Water Losses Reduction in Water Networks*". Waterloss 2009. ISBN 978-1-920017-38-5. Pages 90-97.

Cabrera E., Pardo M.A., Cobacho R., Cabrera E. Jr. (2010) "Energy audit of water networks". *Journal of Water Resources Planning and Management*. ASCE. November December 2010. pp 669-677

Cabrera E., Gómez E., Cabrera E. Jr., Soriano J., Espert V (2014) *" Energy assessment of pressurized water systems"* Under review.

5. HEAT RECOVERY FROM WATER AND WASTEWATER SYSTEMS IN OSLO

5.1 Introduction

This chapter presents heat recovery from water and wastewater as a promising intervention option in Oslo.

Oslo Water and Sewerage Works (VAV) is a municipally-run utility that supplies water (96 million m^3/y) and treats the wastewater of the 625,000 inhabitants of the City of Oslo.

For the period 2000-2006, the energy consumption of the urban water cycle services of Oslo was estimated (Venkatesh & Brattebo, 2011). The per-capita annual consumption of energy in the operational phase of the system varied between 220 and 260 kWh. The direct energy use (electricity and heat) per unit volume water supplied was 0.4 kWh and per cubic metre wastewater treated was 0.8 kWh. The degree of treatment is likely to increase, increasing the energy consumption.

Oslo Water and Sewerage Works (VAV) targets for energy conservation include advanced equipment controls in order to design and implement pump and motor efficiency programs and to optimize the treatment plants processes.

In this research, the main focus lies on energy recovery through the use of heat exchangers and heat pumps at different stages in the network and at the treatment plants, focusing on effluent flows at Hias and BEVAS WWTPs, and the flow of raw water to Oset water treatment plant (WTP). Possibilities for heat recovery on small scales in households and point-recovery in the wastewater network are also mentioned.

Within the treatment plants in Norway there is awareness of the potential of installing heat pumps recovering heat from the water or wastewater. After talking to various plant operators; namely IVAR, MOVAR, and Tromsø municipality, it seems that the concept is known and used in several plants. MOVAR operates two treatment plants with heat pumps installed; Kambo and Hestevold, while in Tromsø Strandveien WWTP recovers heat that is connected to a district heating system serving approximately 600 apartments and 30 000 m^2 of office and theatre spaces with existing plans to expand this to 1200 apartments.

5.2 Theory

5.2.1 Energy potential

Wastewater

In a conventional new building, approximately 15 % of the thermal energy provided to the building is lost, unused, through the sewage system. For a low-energy consuming building these figures are up to 30 %. The greatest single energy losses in buildings of today are the ones going to the sewer (Schmid).

Hence, the total theoretical potential is significant. It is, however, not always feasible to extract all wastewater energy due to quantitative and geographic limitations. The energy available is a function of both temperature and flow rate. The flow rate is a parameter that varies greatly over the network. Local availability of wastewater as a source of energy is also limited. The optimal extraction sites, being economically interesting, are located where wastewater is available in large volumes, with a continuous flow. Typical examples are hospitals, industrial enterprises, housing estates, main pipelines and sewage treatment plants.

Drinking water

As for all sources, the energy potential in drinking water is a function of temperature and volume. For instance, let us assume that the initial water temperature is 4°C, and the water after energy extraction is 2°C. These are cold conditions, typical for a country like Norway. This makes 83.6 kW available per 10 liters/second. A WTP with a flow of 1000 liters per second will then have 8.36 MW of available energy (Steinar, 2013).

When considering drinking water energy extraction one will also face geographic challenges. Distance between heat source and target is decisive for both economy and energy efficiency. In this assignment the focus lies on extraction from the treatment plant. The water treatment plant often has a location isolated from other industrial or commercial areas. But the internal energy demand at the plant itself is usually great, and will make a heat pump system economically interesting.

5.2.2 Concept of the heat pump

One way to make use of thermal energy bound in the water and wastewater is through the use of heat pumps. A heat pump is a unit that transfers thermal energy from a heat source to a heat sink. The heat source will typically have a lower temperature than the heat sink. Thus the second law of thermodynamics, heat flows spontaneously from hotter to colder regions. This is usually shown through equation 1. It states that, for a closed system, the change in entropy (dS) is given by the transfer of heat (δQ) divided by the equilibrium temperature (T). The entropy is either increasing or staying constant, but never decreasing. Hence, the system's desire for equilibrium conditions is driving the heat transfer and increasing entropy.

$$dS = \frac{\delta Q}{T} \qquad (1)$$

dS = change in entropy [J/(K·s)]

δQ= transfer of heat [J/s]

T = equilibrium temperature [K]

(Tipler & Mosca, Physics for Scientists and Engineers (B), 2008)

The heat pump is thereby designed to move the heat energy in the opposite direction of spontaneous flow – against the equilibrium-seeking temperature gradient. The principle is the same as the one used for air conditioning and refrigeration. Accordingly an external amount of energy is required to drive the desired interchange of energy.

The Coefficient of Performance (the COP) of a heat pump describes the pump performance. It simply expresses the ratio between the energy supplied from the heat pump, and the heat pump energy consumption.

5.2.3 Heat exchangers

Heat exchangers are pieces of equipment that are built in order to transfer heat from one medium to another as efficiently as possible. There are various ways of transfer; the heat might need to be transferred through a wall or similar, meaning the two media would never be in contact, or it could transfer heat between media that are in contact.

Heat exchangers are used in a variety of ways in industry, space heating, refrigeration, air conditioning and many others. One example is in a combustion engine where radiators are installed in order to cool down the circulating fluid, by letting air pass through the coils in the radiator thereby heating the air and cooling the fluid.

Heat exchangers are primarily classified in three ways, depending on the flow arrangement of the fluids; *Parallel-flow, counter-flow* and *cross-flow.*

All these types of heat exchangers are suitable to recover heat from the wastewater. An important aspect with all alternatives is the quality of the wastewater. Because of the solid contents, they must all be able to handle that, and be relatively easy to clean and maintain because fouling will occur faster in these kinds of waters than in other sources. It is also important that materials used are able to withstand the corrosive nature of the wastewater.

Also, the use of these heat exchangers cannot be the only contributor to the final user because of the low temperatures of the source. Therefore, the use of heat exchangers will only be to the pre-heating of water, either as a step in or before a heat pump, or, in recovery from grey water in buildings, before the water heater or boiler on the heating network. When it comes to typical efficiencies of the different types of heat exchanger, the values vary depending on setup and size. However, the plate heat exchanger is proven to have a generally higher heat transfer rate than the others.

Table 5.1. Heat transfer rate (Engineering ToolBox)

TYPE OF HEAT EXCHANGER	W/m^2K
Spiral Heat Exchanger	700 – 2500
Plate Heat Exchanger	1000 – 4000
Shell and Tube Heat exchanger	150 – 1200

The plate heat exchanger has the highest heat transfer rate and is also quite versatile; it can be used in all scenarios. Its performance, size, ease of expandability and cleaning make this a very good option with respect to water and wastewater. It is also easily available in suitable materials needed to operate in difficult environments.

5.2.4 Ways of extraction

The most common ways of extracting energy from the water and wastewater system are:

- Utilization WTP influent
- In-house heat recovery
- Utilization of raw wastewater in pipe
- Utilization of WWTP effluent

The potential of heat recovery from water and wastewater is enormous. If all the wasted energy can be recovered, society can benefit a great deal, both environmentally and economically. However, there are some problems that need to be addressed such as what way of extraction is the best. Location is a decisive factor, another is the use of the energy. Will the energy be used for space heating, water heating or for other things? In order to achieve the highest efficiency, low grade energy meaning low temperatures would be most suitable, this would already rule out water heating. Low grade would also mean that peak loads of the heating system would not be handled by the wastewater heat recovery and one would therefore need to have a boiler of some sort.

5.2.5 District heating

There are numerous ways one could use the heat recovered from the water sector. Firstly in the treatment plant itself. For example space heating and heating of digester tanks and other processes in the treatment of the wastewater. In the case of wastewater this would lessen the pressure of the use of sewage gas that is commonly used for these tasks, and one could refine the sewage gas in order to meet the standards for natural gas.

District heating is a system for distributing heat in residential or commercial areas by generating heat in a centralized location. There are many ways of obtaining this heat; the burning of fossil fuels and biomass is the most widely spread. However, there are many other ways of obtaining this heat. A method that is widespread in Iceland is geothermal heating, other places central solar heating is more suitable or nuclear power plant effluent.

When it comes to heating, district heating systems can be more efficient and more environmentally friendly than local boilers (Andrews, 2009).

5.3 Analysis

Examples of heat extraction from water and wastewater have started to appear in Norway in recent years. Hias WWTP in Hamar is one of the national leading institution for heat pump energy recovery in wastewater treatment plants having many years of experience. Oslo Water and Sewage Works (VAV) have also shown interest in intervention technologies by installing heat exchangers in raw wastewater pipes (upstream WWTP), and also by introducing heat pump technology in their main water treatment plant, Oset WTP. The possibility of expanding the energy extraction from another wastewater treatment plant, Bekkelaget WWTP, has also been a matter of consideration.

5.3.1 Hias WWTP

Hias WWTP in Hamar is a WWTP with mechanical, biological and chemical treatment steps. All treatment steps produce sludge. The sludge treatment generates biogas that is used for internal energy use at the plant. The produced biomass is being used as agricultural fertilizer in the surrounding area. The effluent wastewater has been used for heat pump energy recovery for more than 30 years. In 2010 the heat pump system was renovated. Now the heat pump system can deliver an effect of 3 MW and has a projected COP of 6.44. The heat pump is only in use during the winter season, when heating is necessary. It uses ammonia as its working fluid and a modern set of plate heat exchangers. The annual energy delivered from the heat pump system is approximately 40 000 MWh, while the heat pump energy consumption is 6000 MWh per year (SPF ↙ 6.5) (Berset, 2011).

Table 5.2. Key data from Hias WWTP

	DRY WEATHER FLOW (NO RAIN/SNOWMELT)	MAXIMAL FLOW CAPACITY (RAIN/SNOWMELT)
Flow rate	15.000 m^3/d	53.000 m^3/d

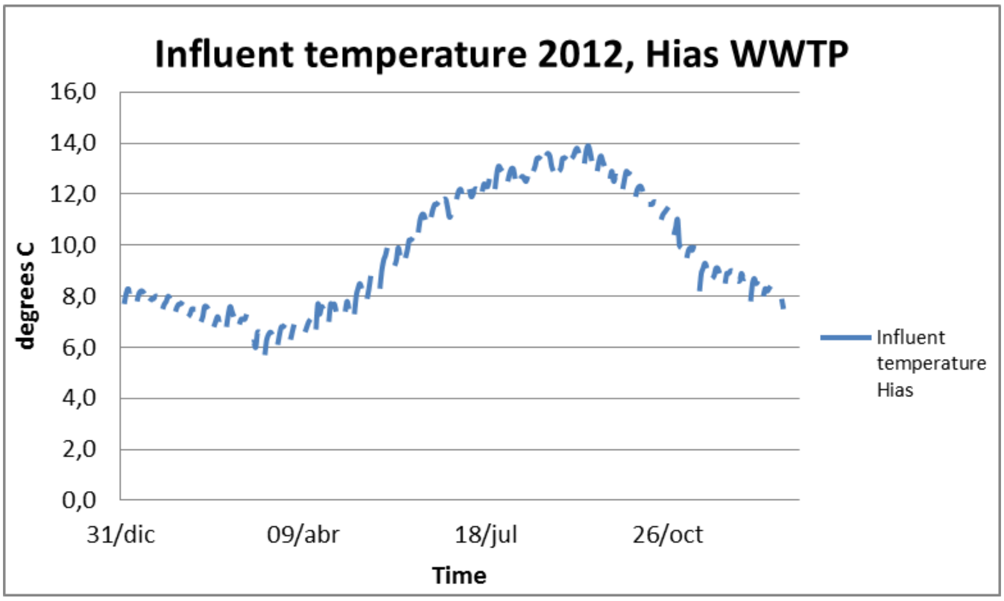

Figure 5.1: Influent temperature at Hias WWTP from 2012

Figure 5.2: Picture from Hias WWTP (the heat pump compressors)

The location of the WWTP is at Ottestad, just south of Hamar. It is situated next to the recipient – the great lake of Mjøsa.

COP and efficiency η

Hias has a projected COP of 6.44. This value is based on the projected temperature lift of 26°C (from 6°C to 32°C). Hence the equations 4 and 5, we can calculate $COP_{theoretical,\ Hias}$ = 11.731 and η_{Hias} = 0.549. Calculations are done below, in calculations 10 and 11.

$$COP_{Hias} = 6.44$$

$$COP_{theoretical,Hias} = \frac{(32+273)\,K}{(32+273)\,K - (6+273)K} = 11.731 \quad (10)$$

$$\eta_{Hias} = \frac{COP_{Hias}}{COP_{theoretical,Hias}} = \frac{6.44}{11.731} = 0.549 \quad (11)$$

If the projected values are the same as the real values, we can estimate that the total efficiency η_{Hias} is 0.549, as shown in the calculation above. We can then extract the graph in figure 5.3 showing the COP as a function of temperature lift from 6°C. COP = 6.44 occurs at the temperature lift of 26°C.

However, reports from Hias states that the temperature of the wastewater running through the evaporator normally has a value of 8-11°C. This means that the actual temperature lift will be of between 21 and 24°C (8-11°C to 32°C). With the lower temperature lift, the actual COP gets higher. Not only will COP become higher with the lower temperature lift, the higher T_{cold} will also contribute to an increase in COP, as discussed in part 2.3.2.

Then, how significant is the difference between temperature lifts from 6°C/8°C/11°C to 32°C, with respect to COP? Figure 5.4 shows a comparison of COP for T_{cold} = 6°C, T_{cold} = 8°C and T_{cold} = 11°C. We can see the difference most relevant for Hias, marked with a vertical line at T_{hot} = 32°C.

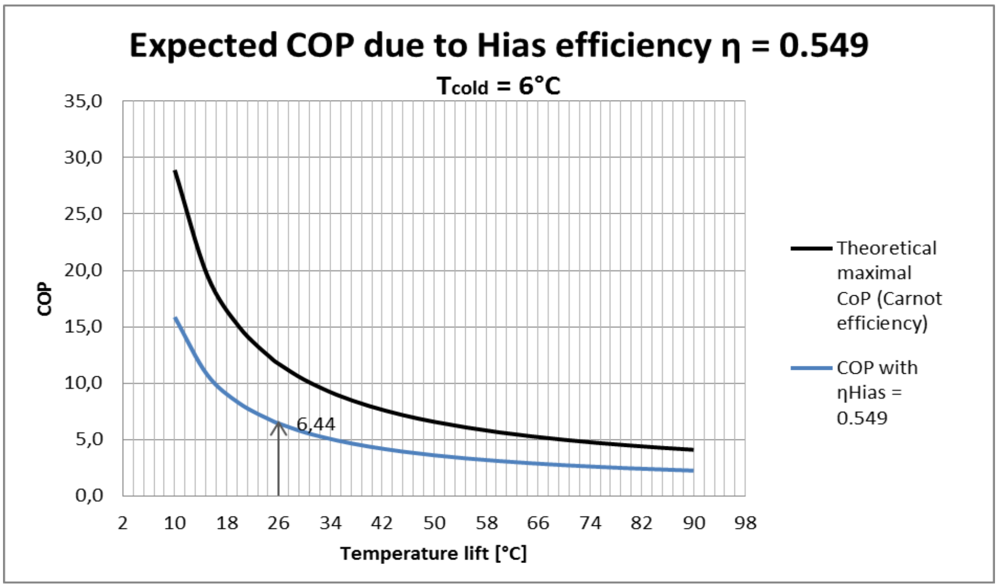

Figure 5.3: Theoretical maximum COP vs Hias COP

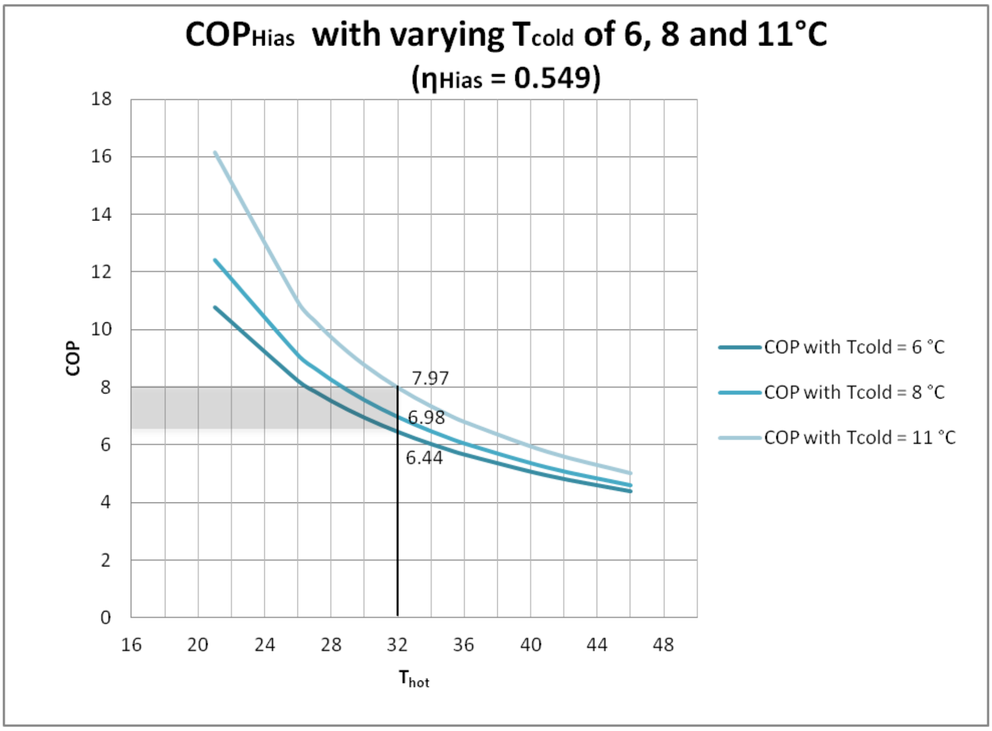

Figure 5.4: COP at Hias for different Tcold values

- The temperature lift from 6 to 32°C gives COP_{Hias_6} = 6.44
- The temperature lift from 8 to 32°C gives COP_{Hias_8} = 6.98
- The temperature lift from 11 to 32°C gives COP_{Hias_11} = 7.97

The staff at Hias reports that the actual COP is higher than the projected 6.44. They estimate an average of a little more than 7. This makes sense with figure 5.4 – As long as the effluent wastewater has a temperature above 8°C, COP is above 6.98. It therefore seems that the projected quality of the system responds to the real conditions, with a total efficiency of η_{Hias} = 0.549.

Seasonal performance factor (SPF)

Hias can report an SPF value of 6.5 from their system; the plant receives heating power equal to 6.5 times the amount of the bought heating energy. This results in an annual reduction of heating costs of $1- 6.5^{-1}$ = 84.6 %. This achievement led them to a repayment period of 3.6 years at the project as a whole (Berset, 2011). With an SPF value at 6.5 and a corresponding average COP-value at about 7, Hias has a relatively low energy amount consumed by the peak load heating unit. They do not know for sure the exact fraction of the annual heat energy covered by the peak load heating unit. But based on the SPF = 6.5 and the COP_{hp} = 7 this fraction must be of between 0.1 and 1.3 %. Applying equation 6, assuming the efficiency of the peak load unit to be (η_{pl} = 1), this fraction (α_{pl}) will be 1.3 %. We can thus state that the heat pump itself delivers at least 98.7 % ($\alpha_{hp} = 1 - \alpha_{pl}$). The peak load heater is only in use when maintenance is performed.

5.3.2 Oset WTP

Oset water treatment plant in Oslo is the largest water treatment plant in Scandinavia and Europe's largest in a mountain. The WTP was renovated and the new part of the plant was opened September 18, 2008. Today 90 % of Oslo is supplied with drinking water from this plant (Oslo Kommune, 2012).

Table 5.3. Key data from Oset WTP

PARAMETER	MINIMUM	MAXIMAL
Flow rate	6.000 m^3/h (night)	16.500 m^3/h (morning)
Temperature on raw water	2.6⁰C (March/April)	9⁰C (October/November)

The plant had to be improved in order to meet the standards set by *"Drikkevannsforskriften"* where one of the requirements states that there should be two hygienic barriers on the drinking water. The new Oset WTP fulfills the requirements by basing its treatment on chemical precipitation in Actiflo as well as UV-treatment (Oslo Kommune, 2012).

With the new plant heat pumps were installed in order to heat the spaces inside the mountain as efficiently as possible. These work by utilizing the heat energy in the raw water prior to treatment by leading the raw water into a heat exchanger before returning to the normal flow through the treatment plant. On the other side of the heat exchanger there is a closed loop that is connected to the heat pump. The heat pump is based on ammonia as working fluid and boosts the temperature of the water on the heat circuit by extracting the heat from the closed loop. In order to boost the temperature of the water on the heating circuit to an acceptable level, a boiler has been installed to contribute during peak loads. The heated water circuit is connected to the ventilation system through heating batteries and the temperatures in the mountain are controlled through these.

Figure 5.5: Picture from Oset WTP (Plate heat exchanger)

The location of the WTP is, compared to many others of its kind, situated close to urban areas. However, the settlements nearby are predominantly individual residential housing in an already developed area. In immediate proximity to the plant, the area is mostly forested and undeveloped. However, due to Oslo Municipality's strict policies on the forest boundaries in Nordmarka recreational area and the location close to a vital drinking water source it is very unlikely that these areas would be urbanized and/or especially industrialized in the foreseeable future.

The external use of the heat recovered from the raw water in this instance would likely not be applicable because of the vast cost of installation in already developed urban areas, especially with individual housing. But for heating their own spaces the use of heat recovery is important and saves a lot of expenses in terms of energy because of the large spaces in the mountain.

COP and efficiency η

The operators of Oset WTP do not know the COP or the efficiency η of their system. We know however, that the temperature of the raw water (T_{cold}) lies in the interval of 2.6°C - 9°C depending on the season. This shapes the theoretical COP together with the T_{hot}. At Oset WTP T_{hot} is projected to be 55°C (Mohn, 2013). This leads to a $COP_{theoretical}$ between 6.3 and 7.1. The efficiency η of the system is unknown. The new heat pump system started operating in 2008. This is of similar age as the one at Hias (2010). Let us make the assumption that Oset runs their heat pump with η_{Hias} = 0.549 in order to get an impression of what range it is possible to be in with respect to COP. As shown in figure 29, this result in a COP between 3.44 and 3.91.

At Oset WTP, 05.03.2013, the heat pump system was running with data software monitoring important physical values, indicating that T_{cold} = 3.6 and that T_{hot} = 52.6. Assuming the η_{Hias} = 0.549 this means an instant COP value at 3.65 as presented in figure 5.6.

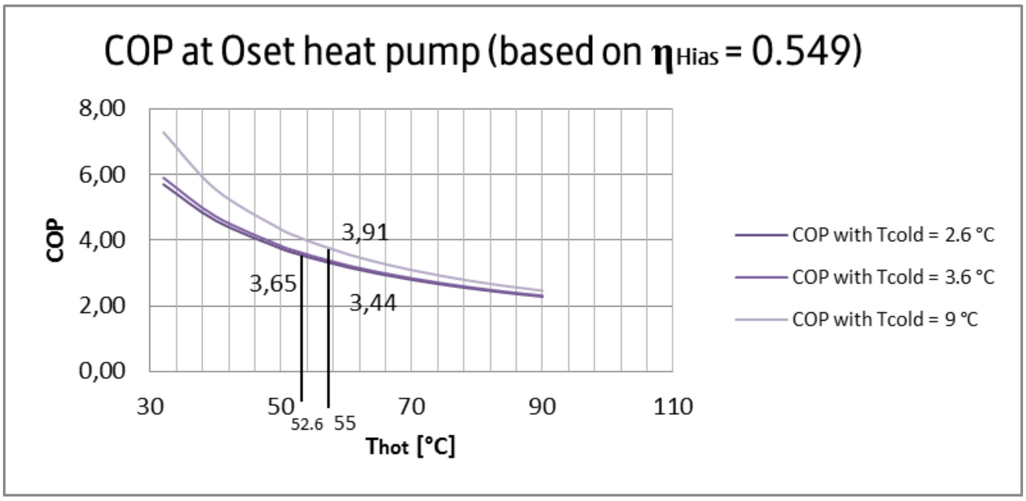

Figure 5.6. COP at Oset WTP based on Hias efficiency

Seasonal Performance Factor (SPF)

The peak load system supplies 37.5 % of the heat on the day of 05.03.2013. This will clearly lead to an SPF lower than the COP value. The operators at Oset cannot report any average value of the contribution from the peak load heater. But they say it is always running, and that 37.5 % is a typical value (Mohn, 2013). If we assume this value to be representative (α_{pl} = 37.5 %) over the entire season we can obtain an SPF value for the system through equation 6. In this case the heat pump contribution is α_{hp} = 62.5 %. Annual mean COP_{hp} is here set to be 3.65, once again assuming heat pump efficiency of η_{Hias} = 0.549 and peak load heater efficiency of η_{pl} = 1, and that the situation of 05.03.2013 is representative for the whole season. Applying equation 6 this leads to a maximum SPF factor of 1.83 (calculation 12).

$$SPF_{COP=3.65} = \frac{1}{\left[1 \cdot \left(\frac{0.625}{3.65} + \frac{0.375}{1}\right)\right]} = 1.83 \qquad (12)$$

Comments

In the old plant at Oset, there is still no such heating system, and connecting this part of the plant could be an idea that would be worth taking a closer look at. At the moment this part is heated by electrical boilers.

Using a heat pump and extracting heat from raw water is very effective, but an important aspect one has to take into account when it comes to efficiency is having a ventilation system that is up to date. Old ventilation would just let the air inside the buildings out, basically wasting the heated air. With newer and improved systems the energy heat in the inside air is recycled on its way out, and by that reducing the wasted energy.

Keeping in mind, that the numbers found in part 3.2.2 and 3.2.3 depends on numerous presumed conditions, it still draws a picture of how the situation *might be*. One inevitable fact is how the use of peak load system is limiting the SPF. There might, however be good reasons for this application, as discussed in 2.4. The temperature lift from between 2.6 and 9 to 55 is greater than the temperature lift at Hias, being another factor making the COP value lower at Oset WTP than at Hias. If the guesstimated SPF of 1.83 is correct, Oset WTP reduce their energy costs by $1- 1.83^{-1}$ = 45.4 % with their use of heat pump energy recovery.

Oset WTP access data software monitoring the heat pump system. Neither the plant operators nor the municipality engineers have any estimate of the COP or SPF of the system. The data software might be able to extract information leading to a better understanding of the performance and optimized operation of the heat pump. Clearly, providing hygienically safe drinking water is the main objective at Oset WTP, and should always be of highest priority. But although it is not yet done, Oslo Municipality say they wish to investigate the performance of the heat pump system soon (Rommetveit, 2013).

5.3.3 Bekkelaget WWTP

Bekkelaget WWTP in Oslo is a WWTP with mechanical, chemical and biological treatment steps. The plant has biological removal of nitrogen. The treatment plant was renovated in 2001 and now treats wastewater that equals the amount of 290 000 pe, where 30 % constitutes of industrial wastewater. This means that the plant is the second largest of its kind in Norway. The wastewater effluent is released in the Oslo fjord through a pipe at 50 meters below sea level. Because of the size of the plant and the location, it is imperative that the effluent is of the highest quality possible, otherwise the recreational areas in the fjord and the biodiversity would be negatively affected (BEVAS).The treatment plant has taken measures that mean they produce more energy than they use, one is the production of biogas.

All different treatment steps produce sludge which is again heated and treated in decay tanks. This helps to produce biogas that again is refined to achieve a quality of the gas that can be utilized by vehicles. Through this, the treatment plant is able produce 20 GWh of biogas, enough to power 80 buses, thereby contributing to save 3700 tons of climate gases per year. Heat pumps, that use excess heat from the biogas refinery, help the decay process by heating the sludge from 25°C to 55°C. The sludge is also used in agriculture as fertilizer (BEVAS).

Table 5.4. Key data from Bekkelaget WWTP

	DRY WEATHER FLOW (NO RAIN/SNOWMELT)	MAXIMAL TREATED FLOW CAPACITY (RAIN/SNOWMELT)
Flow rate	90.000 m^3/d	164.160 m^3/d

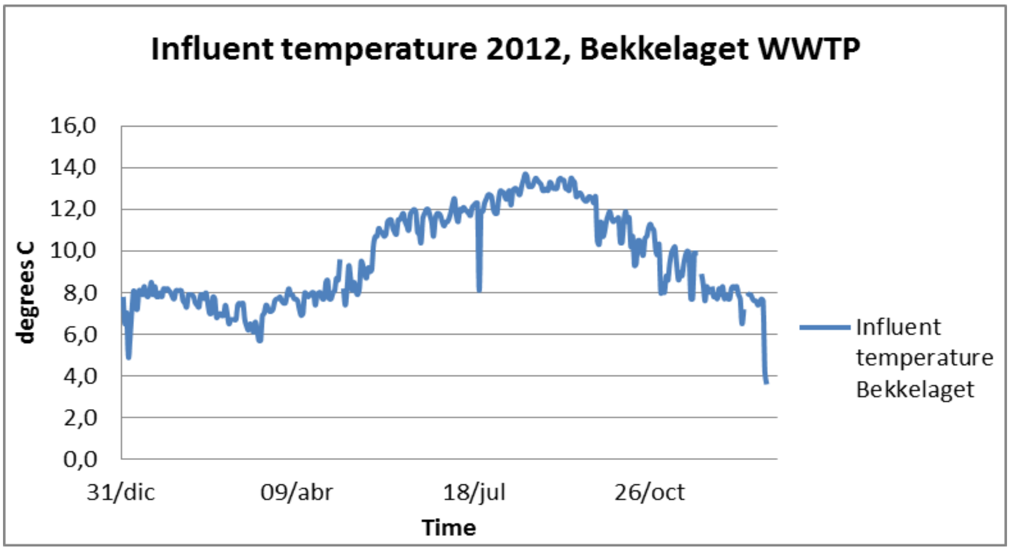

Figure 5.7: Influent temperatures at Bekkelaget WWTP in 2012

Figure 5.8: Picture from Bekkelaget WWTP (Activated Sludge system)

Bekkelaget WWTP is located 3 kilometers south of Bjørvika and the Oslo Opera. The recipient of the WWTP is the Oslo fjord.

Energy extraction potential at Bekkelaget WWTP

Even though measures have been taken in order to recover energy, there is still an enormous potential of recovering heat from the wastewater effluent.

Could Bekkelaget benefit from extracting energy from their effluent? To answer that question, one has to look at all practical, environmental and economical aspects. The first and fundamental criteria, is the energy potential. Comparing Bekkelaget WWTP and Hias WWTP we see differences in hydraulic conditions. Bekkelaget will after the opening of the projected new tunnel have an expected Q_{avg} of about 45 mill m^3 per year, whereas Hias has about 6.6-8.5 mill m^3 annually. However, hydraulic access is not always relevant in this question, as only a fraction of the flow is used. The extraction of heat can be proportionally increased with the increase of heat pumps. For instance, at Hias WWTP, 80 l/s to 165 l/s (about 30-70 % of the effluent) runs through the heat exchangers depending on the flows (Hagelund, 2013). With the installation of another heat pump they could increase their production of yet another MW. In other words Bekkelaget should have enough volume of effluent water to extract a much greater amount of energy than Hias does.

Energy potential in effluent

The expected energy amount from Bekkelaget WWTP has been studied by the Norwegian think tank Civita. They have studied the possibility of supplying the developing commercial area of Bjørvika with energy. They report that 47 GWh per year can be expected when aiming to extract energy both for heating and cooling purposes (Næss, 2008).

Expected energy efficiency

Whether energy can be extracted with a reasonable efficiency is dependent on the technical solution; which types of condensers are used for example? As Hias installed a modern heat pump system in 2010, it makes it a natural object for comparison. Let us assume that they in Bekkelaget install the exact same equipment of condensers, compressors, evaporators etc. Could they experience the same success as Hias? Let us first take a look at the effluent temperatures at the respective WWTPs.

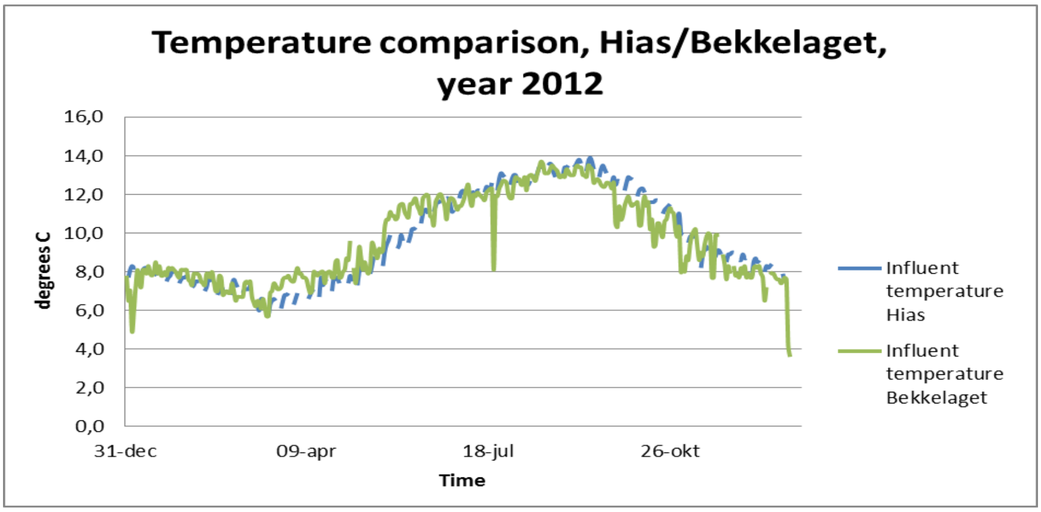

Figure 5.9. Temperature comparison between Hias WWTP and Bekkelaget WWTP

Figure 5.9 shows an influent temperature comparison between Hias and Bekkelaget. It is assumed that the influent temperature has the same relationship to the effluent temperature in both plants. We can extract the following statistical conclusions based on the data from 2012:

Table 5.5. Statistical comparison between Bekkelaget WWTP and Hias WWTP data

PLANT	AVERAGE TEMPERATURE	STANDARD DEVIATION
Bekkelaget WWTP	9.64°C	2.25
Hias WWTP	9.76°C	2.39

As both figure 5.9 and table 5.5 suggest, the temperatures at Bekkelaget are very similar to the ones at Hias. This comparison only takes the year of 2012 into account. However, based on the 2012 data, it is fair to make the assumption that Bekkelaget has the same temperature conditions in their effluent as Hias.

If the assumptions of similar heat pump system and effluent water are met, we can assume Bekkelaget WWTP to get the same pump efficiency as Hias. Hence part 4.1.1, the pump efficiency was estimated to be $\eta_{Hias} = 0.549$. As mentioned in 3.4.1, one imagines a combined heating and cooling system deriving from the heat pump at Bekkelaget. A combined solution will normally have lower pump efficiency than for a pure heating heat pump. However, with a more modern and a larger scale heat pump than the one at Hias, the efficiency can be expected to be higher. We therefore assume these factors to cancel each other out, continuing to suppose a pump efficiency of η_{Hias} = 0.549.

Potential uses

For Bekkelaget WWTP it is possible to imagine the following ways of using the thermal energy from the cleansed wastewater effluent:

- A *high temperature* (80-90°C) district heating system using heated water, to the commercial areas of Bjørvika and Kværnerbyen, possibly even connecting to the existing regional district heating system in Oslo. This would require cooperation with Hafslund, as they have the license for distribution of heat in the area.

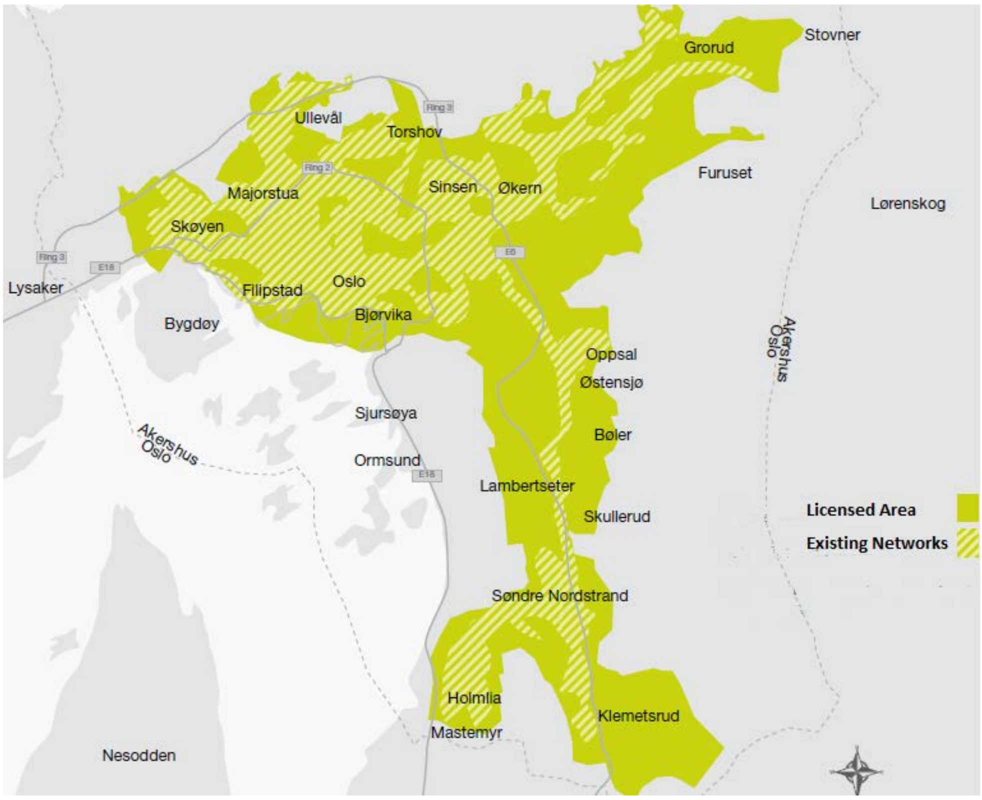

Figure 5.10: Map of existing networks and current licensed area for expansion by Hafslund (Hafslund, 2013)

- A new *low temperature* (32°C) district heating system using heated water in established nearby residential areas such as Norstrand, Ekeberg and Bækkelaget.
- In-house heating for treatment steps in the plant, notably the biological steps and/or the sludge treatment (unknown degree of heating, depending on the exact purpose).
- In-house heating for the spaces, a total volume of 380 000 m^3 of space has been excavated in the mountain in Ekebergsskrenten (32°C).
- Heating of water for domestic use (60°C).

For these above purposes we can expect temperature lifts to roughly 32, 60 and 85°C depending on the purpose. As we can see from figure 5.11, the temperature in the wastewater has a minimum value around 6°C and a maximum around 14°C, with an average of 10°C. What COP values could we expect for these temperature lifts, assuming a total efficiency of η = 0.549? How will COP vary from minimum, average and maximum T_{cold} (6, 10 and 14)? The diagram in figure 36 show assumed COP for these conditions.

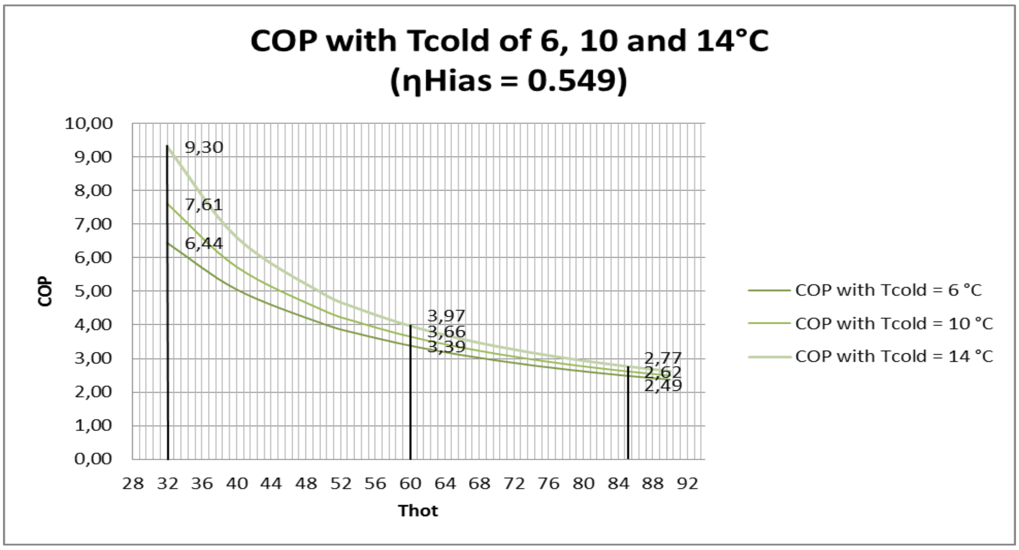

Figure 5.11. COP values imaginable for Bekkelaget based on Hias conditions

The total energy efficiency of the imagined Bekkelaget WWTP would ultimately be captured within the SPF value. The SPF is limited by the COP value, and dependant on the application. Again we assume a situation similar to the one at Hias WWTP, where the relationship between average COP and SPF is at a ratio of 7 to 6.5 (calculation 13). This simplified interpretation leads to calculation 14. An average COP value at 6.44 will for example result in an SPF at 5.98.

$$SPF = COP_{avg} \cdot 6.5/7 \quad \textbf{(13)}$$

$$SPF_{COP=6.44} = 6.44 \cdot 6.5/7 = 5.98 \quad \textbf{(14)}$$

Using the assumption that Bekkelaget WWTP can obtain the exact same operating conditions as Hias WWTP, we can set up table 5.6. Here we set up the 5 proposed energy uses with corresponding assumed heat sink temperatures. The source temperature lies in the interval of 6°C - 14°C.

Reading table 5.6, one has to keep in mind all the underlying assumptions, making every number uncertain and possibly not realistic. Looking at the SPF-values alone, we see that the energy could be efficiently extracted for different purposes. However, one aspect not considered here, is the economical aspect in relation to installation of the required instruments and infrastructure for the different uses. For instance, the creation of a new *low temperature* district heating system would undoubtedly require great investment. Hence table 7 illustrates a great potential, but has to be supplemented with more precise studies before making the decision of installing a new heat pump and or a district heating system.

Table 5.6. Overview of proposed uses of recovered heat from Bekkelaget WWTP

TYPE	CONNECT TO EXISTING DISTRICT HEATING SYSTEM	CREATE NEW DISTRICT HEATING SYSTEM	IN-HOUSE HEATING FOR TREATMENT	IN-HOUSE HEATING FOR THE SPACES	HEATING OF WATER FOR DOMESTIC USE
Description	A *high temperature* (80-90°C) district heating system using heated water, to the commercial areas of Bjørvika and Kværnerbyen, possibly even connecting to the existing regional district heating system in Oslo.	Distribute heat using heated water in established nearby residential areas such as Norstrand, Ekeberg and Bækkelaget.	Heating for treatment steps in the plant, notably the biological steps and/or the sludge treatment.	Heating for the spaces, a total volume of 380.000 m^3 of space has been excavated in the mountain in Ekebergsskrenten	Heating water for domestic use at the WWTP.
Ca. heat sink temperature	↙ 85°C	32°C	Unknown	32°C	60°C
COP (assuming Hias conditions)	2.49 - 2.77	6.44 - 9.30	Unknown	6.44 - 9.30	3.39 - 3.67
SPF (assuming Hias conditions)	2.31 - 2.57	5.98 - 8.64	Unknown	5.98 - 8.64	3.15 - 3.41

5.4 Discussion and conclusion

5.4.1 Discussion

District heating

The potential of using the heat from water and wastewater for district heating is great, however, it depends a lot of plans for infrastructure and building. The cost of implementing a district heating system is substantial and can vary greatly depending on the layout of the area where the system is going to be implemented. A system in an area with detached houses and villas would require a large investment cost due to the high number of connections needed relative to the number of recipients one would reach. If this area already has a developed infrastructure, the investment would be even more costly as one would not be able to combine the installation with other works on infrastructure such as water and wastewater mains. But if the area set for a district heating system consists of commercial or large apartment buildings one would reach far more recipients and the payback period would be considerably shorter, especially if the area is new, and has existing plans for improvement and/or expansion in the infrastructure.

Another question which needs to be taken into account when it comes to district heating is whether to have high or a low temperature system. For a low temperature system, the cost of installation would be greater due to the fact that one needs to install heat pumps in every building in the area, in order to boost the temperature to a respectable level for heating. The upside of a low temperature heating system is the fact that the losses of energy are lower on the circuit. On the other hand, in Norway, where the circuit temperature in district heating systems range between 80 and 90 Cthe losses only account for 5-10 % (Sweco Grøner, 2007), and these kinds of systems only require one centralized heat pump, before sending the heated water around the circuit. Generally, a large heat pump is considered to have a better performance than smaller ones. All in all, one could argue that a high temperature network with a centralized heat pump or boiler would be the most cost efficient alternative, especially in areas that are under construction such as Bjørvika and Kværnerbyen.

An important aspect that should be considered when a district heating system is being developed is the energy demand due to pumping. A negative aspect of district heating systems, some would argue, is the fact that lower energy prices for heating does not necessarily lead to lower final individual expenditure, but rather that individuals use more energy, because of its abundance.

Bekkelaget

At Bekkelaget treatment plant the potential for energy recovery is great, with a large flow of wastewater effluent that can be cooled to a great extent. The use of this energy for district heating could involve a network constituting of the nearby areas of Ekeberg, Nordstrand and Bekkelaget. A district heating system in these areas would lead to lower energy consumption with respect to heating, and also an income for the municipality or BEVAS. But at the same time the cost of investment in this area would be substantial as the areas mainly consists of detached houses and villas, in addition to it being an already developed area. Therefore, implementing a distict heating system in these areas would most likely be considered too costly. Another possibility for a district heating system is to use it in Kværnerbyen and Bjørvika closer to the centre of Oslo. These areas are largely under construction currently, with plans of large apartment buildings and commercial buildings. These types of buildings are ideal when it comes to district heating and the wastewater at Bekkelaget would be a good source of heat, considering the relatively stable temperatures and the seemingly infinite potential. However, this area, with its proximity to the sea, can use seawater as a source of heat for district heating as well, and with that having an even more stable temperature than the wastewater and its location closer to the given area, it has been considered to be a more suitable source. Nevertheless, the performance of the heat pump system would be considerably lower as heat pump systems using seawater as a source would operate on lower temperatures than that of wastewater source.

When it comes to Bekkelaget treatment plant, one could also use the effluent as a heat source for in-house heating. There are large spaces inside the mountain that could potentially be heated using heat pumps. Also, one could, as has already been introduced in the production of biogas and through the fermentation process, use the heat recovered from the effluent to heat the treatment processes of the wastewater that would benefit from a rise in temperature, notably biological treatment steps. In addition to heating spaces and processes within the plant one could use the thermal energy to heat the water in the tap, removing, or at least diminishing the need of electricity for the water heaters.

Oset

District heating could be a possibility here as well; it could easily be compared to heat pumps using seawater as a source, with generally equal temperatures. However, due to its relative remoteness and the characterization of the nearby developed areas, a district heating system would be quite inefficient as well as requiring large investments; hence it is not considered to be a very good option. There is no immediate plan for development in the area around the plant either, so increasing the potential of the already existing heat pumps would largely go to heating the premises, with the possibility of expanding to the old parts of the plant that now act as an emergency option in case the operating plant for some reason should fail. In addition to heating the spaces one could also connect the heat pump to the water heater in the plant, reducing the cost of electricity for heating.

Hias

As we can see from the analysis, the heat pump system implemented at Hias is very efficient with respect to COP and SPF. The potential of energy recovery is still great, having a surplus of produced energy, and possible uses one could implement here are greenhouse or other facilities that could be situated nearby. There are plans to use the energy to heat water for domestic use as well, thereby needing another heat pump to boost the temperature higher.

District heating could also be an option here. In this area, a district heating system taking heat from the wastewater effluent could have a great effect if new residential areas were to be built nearby. In order for that to be most efficient, one could have houses with a design that could use low temperature water, meaning the same temperatures as in the heating circuits at the plant, for example under-floor heating. This type of heating would have smaller losses on the network and a higher COP in the centralized heat pump.

Heat recovery directly from mains

There is a great potential with heat recovery directly from the mains, because it is extremely flexible when it comes to location. In populated areas there are pipes everywhere, and if there are plans of building sports halls, shopping malls, large apartment housing or commercial buildings in an area close to a main with large flows of wastewater, a system that could utilize heat energy in the wastewater flow could be ideal. This concept is widely used, but it is not as energy efficient as extracting heat from the wastewater effluent. The reason for that is the fact that the temperature of the wastewater affects treatment efficiencies in the treatment plant. This leads to a restriction in how much heat one can extract directly from the mains.

From grey water

From grey water the potential of heat recovery can actually return the cost of investment from 2.5 to 7 years depending on how often the system is used according to the US department of energy. This is on a small-scale level and the larger the building or institution the potential of energy recovery is larger.

5.4.2 Conclusion

The energy potential recovery in the water sector is enormous and a largely unused source of renewable energy. With a predicted rise in energy prices the return time on the investment of installing devices such as heat exchangers and heat pumps in treatment plants as well as in the networks will shorten considerably. The highest potential lies within the large-scale examples such as wastewater effluent and recovery directly from the sewer mains, combined with district heating.

District Heating

District heating is an efficient way of heating spaces and water for domestic use because it uses types of energy that in many cases would go to waste. The situation in Norway, with district heating accounting for only 4 TWh (2009) on a national level, is very low considering the benefits of such systems. The problem in Norway has been the low energy prices and the general assumption that the electricity here comes from renewable sources. However, with Norway being part of a globalized world, with no borders for energy, one should start looking into ways of conserving energy in all aspects of society, with space heating being a major part. District heating is an excellent option for energy saving, and, in our opinion, all developing areas should implement a district heating system, preferably based on sources of energy that would otherwise go to waste.

Wastewater effluent

A good example that shows the energy potential in treated wastewater is the Hias WWTP. The wastewater is standard and comparable with most wastewater in Norway in terms of temperature. Of course, the treatment plant is well suited to utilize the energy extracted which gives them a very short return period on their investments. The example from Hias shows that the energy potential for Bekkelaget is great with very similar temperatures and its relative proximity to developing areas in the center of Oslo that in our opinion, from an energy-conservation point-of-view, should use a district heating system for heating the new apartments and office spaces. The potential when using the wastewater as a heat source is, in our opinion, better than using the seawater as a source of heat when solely looking at performance of the heat pumps. The temperature is considerably higher in the wastewater effluent than that of the seawater, and with a distance of only three kilometers, the extra cost of investment should be returned within a reasonable time.

Bekkelaget can also use the heat recovered for themselves, making the treatment plant even more energy efficient, ultimately producing more energy than their own consumption.

Raw wastewater

Energy recovery from wastewater mains is an option that should be considered whenever there are plans for construction of large buildings or other types of constructions with a demand for heating. If a newly constructed area can be connected to such a heating system, extracting the heat from raw wastewater, one has to make sure the requirements set by the treatment plants are maintained, with respect to limits on heat energy extracted from the wastewater as the temperature has such an important influence on the treatment efficiencies.

All in all, we feel that recovery of heat from the water sector should be prioritized as the potential is at such a high level. This will contribute to the overall reduction in carbon emissions globally that gets ever more important and evident as natural disasters become more frequent with climate changes. One should do everything possible in order to fight this problem and energy conservation and recovery within the water sector and district heating are, in our opinion, helpful contributors. We feel that coordination and cooperation between every level, whether on domestic, local, regional, national and even international level should be considered because then one can explore different ideas and learn from experience of others. Water users at all levels contribute to the total energy consumption, and all should contribute in order to save as much as possible; recovery from grey water on domestic level and through the treatment plants, whether it is water treatment or wastewater, as well as recovery from the mains. The more energy that is recovered from these sources, the better the effect on carbon emissions.

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6. THERMAL ENERGY IN THE WATER CYCLE IN AMSTERDAM

6.1 Introduction

The municipality of Amsterdam has set targets for CO2 emissions. In 2014 the emission level has to be stabilised and from 2015 onwards CO2 emissions should be reduced every year to a level that is 40 % lower than the reference level of 1990. The absolute target is an emission level of 2,480 kton CO2 per year in 2025. That means after 2012 a reduction of 2,102 kton per year has to be established. To achieve these ambitious goals, Amsterdam has an extensive program on reduction of energy consumption, increase of the use of sustainable energy sources, application of sustainable heating and cooling, clean public transportation etc.

Waternet, the water cycle company of the Amsterdam, has the ambition to contribute to these goals. Their ambition is to achieve a climate neutral water cycle by 2020. This means that they have to compensate for an emission of 53,000 ton CO2-eq per year (van der Hoek 2012). First calculations have revealed that energy recovery from the water cycle in and around Amsterdam can result in an emission reduction of greenhouse gases of 74,900 ton CO2-eq per year, among others by linking their water function to thermal energy systems and by utilising the energy potential present in organics in the wastewater. It is estimated that the water cycle can contribute for approximately 2.4 % to the municipal targets mentioned above. In the past years Waternet has conducted research on the possibilities to supply heat or cooling capacity from piped systems (sewers, drinking water mains, pretreated water mains). Recent research, reviewing and comparing the energy demand of several stages in the water cycle in several countries, revealed that 80 % of the primary energy involved in the water cycle is related to water heating for domestic use (Elías-Maxil *et al*. 2014). Systems utilising thermal energy therefore can have a large contribution to compensate greenhouse gas emissions. Results from studies in Amsterdam are described below.

6.2 Drinking water systems

Drinking water mains can either be used for recovery of heat or to provide cooling capacity. This can be done either in a direct mode where the thermal energy is directly transferred to or from the drinking water system of indirectly, using an Aquifer Thermal Energy Storage (ATES) system. In many cases the demand and supply side capacities do not match. Using ATES can increase the available thermal energy or cooling capacity and ‘disconnects’ the temporal variations on demand and supply side. Two case studies conducted in Amsterdam are presented here, both using a system coupled to an ATES.

6.2.1 Plantage de Sniep, Diemen

In Diemen, a suburb of Amsterdam, a feasibility study is done on the recovery of heat from a drinking water transport mains (Meer *et al.* 2010, Mol *et al.* 2013). In Diemen a new residential area is developed called ‘Plantage de Sniep’ (1,200 dwellings). In this area space heating of the dwellings will make use of ATES. Heating is required during winter times and the heat can be abstracted from the ATES system. During the summer the ATES system can be recharged again with excess heat. The drinking water mains can be one of the heat sources to recharge the ATES system. The drinking water in Amsterdam is produced from surface water and varies in temperature between 4 and 22 °C. Especially during the summer months, heat can be extracted, which will have an additional positive effect for drinking water quality. The total system is explained in Figure 6.1.

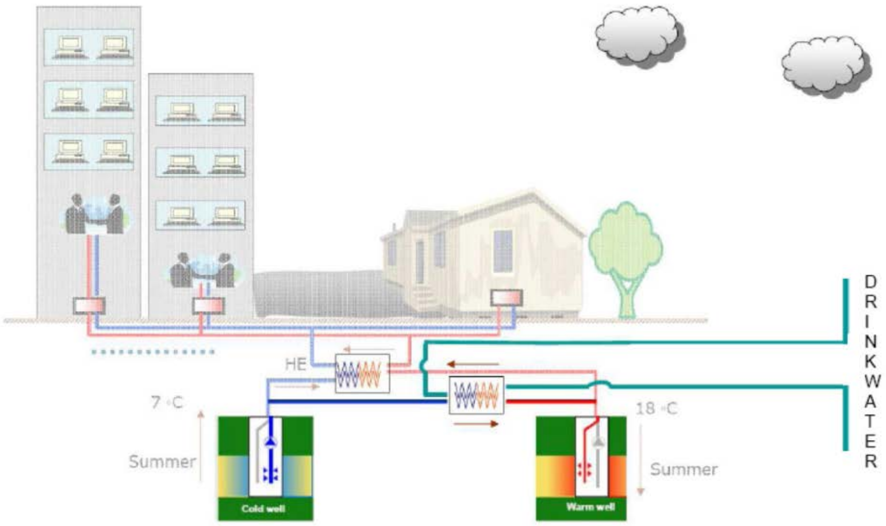

Figure 6.1. Thermal energy supply system including ATES with heat recovery from drinking water.

For Plantage de Sniep the two sources of the ATES system are constructed at a depth of 150-175 m. The cold source has a temperature of 8 °C and the warm source of 15 °C. The feasibility study has addressed the possible effects and risks of heat extraction water quality.

In the winter time, thermal energy from the warm source is abstracted to a local network. Heat pumps at the dwellings take the heat form the network for space heating and preparation of warm tap water. The water in the source network is cooled down and stored in the cold source.

During summer the situation is reversed. The source network is fed from the cold source and used to cool the dwellings. The heated water in the source system is stored in the warm source. Because the heat demand in the winter time is higher than the heat supply from cooling in summer, an additional heat source is required to balance the system. The drinking water mains can provide this additional heat.

To realise the system, it has to fulfil a number of preconditions and constraints. The most important one is that the system may never interrupt the drinking water supply. This requires mainly technical measures like the use certified materials, special demands on pressure (fluctuations), low flow restrictions and a minimum temperature after cooling of 10 °C. Also some special measures for maintenance have to be obeyed.

The available heat capacity from the drinking water system depends on the seasonal variations and the minimum temperature after cooling (i.e. 10 °C). Figure 6.2 shows the period when heat recovery is possible. Depending on the flow and conditions between 21,000 and 36,000 GJ can be extracted. From the design of the dwellings and the ATES system it is expected that approximately 15,700 GJ additional heat is required to balance the system. It is concluded that the drinking water system can fully supply this.

Figure 6.2. Seasonal temperature variation in drinking water in Diemen. The period when heat recovery is possible is shown in blue.

Although no scientific research is known that deals specifically with the question of effects of cooling of drinking water on the microbiological activity, it is expected that cooling will improve water quality, because microbiological growth will slow down. Furthermore, the calciumcarbonate saturation index may be altered somewhat by the cooling of the water: the SI will increase a few hundreds.

Special attention may be required for the heat exchangers. However if the right construction materials are selected and design principles are used that prevent stagnant zones, no problems are expected here either. Another important consideration to be made is leakage from the source system to the drinking water side. To prevent this, a double walled heat exchanger should be used and the pressure at the drinking water side must always be higher than the heat distribution side.

The effect of cooling of drinking water also means that consumers downstream of the system will receive cold water during summer. That means that they will use more energy to produce warm tap water and the CO_2 emissions will be higher. On the other hand, the water in the distribution mains will heat up again by heat transfer from the surrounding soil. The area receiving colder water is therefore limited. Calculations show that the additional

CO_2-emissions coming from extra required heating for warm tap water is below 1 %, while the emission reduction by the system itself is 25-35 % (400 ton CO_2 per year).

6.2.2 Drinking water for sustainable cooling of buildings

In a second more general study, commissioned to the University of Utrecht, the feasibility of using drinking water for cooling has been studied (Volpe *et al.* 2012). In this case the drinking water system is used to remove excess heat. Also in this system the cooling is combined with an ATES system.

The system can be used to restore the balance in ATES systems used for cooling. During the winter months additional cooling capacity can be created by cooling down the water in the cold source of the ATES system. The heat is transferred to the drinking water system heating up the drinking water. The central question in the study was:

To what extent is it socially, economically and environmentally feasible to provide the city of Amsterdam with cold extracted from the drinking water system and stored in ATES, in order to reduce the current energy use?

A multidisciplinary approach was used. In the first place a stakeholder analysis was performed. Moreover, the potential cooling capacity was estimated as well as location for use. Also water quality effects were investigated, especially the risks for *Legionella* spp. growth and finally the societal costs and benefits were determined.

Also in this case seasonal temperature variations of the drinking water were assumed, with variations between 4 °C in winter to 22 °C in summer. The number of ATES systems in use in Amsterdam is increasing, but many of them have an unbalance because more heat is stored than is abstracted. By using cooling capacity from the drinking water mains systems can be brought back in balance. Current legislations requires the system to be balanced at least once per ten years.

The study started with a detailed stakeholder analysis. Special focus was on players not directly involved as a user of the cooling capacity. The importance of this stakeholder analysis is to determine and control risks. Four important aspects have been identified that may have contradictory issues for different stakeholders:

1. CO_2 emission targets
2. Unbalanced ATES
3. (Secundary) effects of the use of drinking water for cooling
4. The role of a water utility, *in casu* Waternet, on the energy market

Beside the identification of the stakeholders themselves, it was also determined how much power they have to influence the application of cooling by drinking water. The most important stakeholders with large influence are the municipal government, the provincial government and the national government (Ministry of Infrastructure and Environment). Furthermore energy suppliers, ATES-system suppliers, and ATES operators are important stakeholders. Figure 6.3 shows the power versus interest matrix for the most important stakeholders.

An important issue for application of drinking water for cooling are the effects for water quality. The most important point is that the drinking water temperature will increase. This results in a reduced biological stability of the drinking water involved as bacteria will grow faster. An important risk is the growth of pathogens especially *Legionella* spp. However, as long as the water temperature stays below 25 °C (maximum temperature of drinking water at the tap, (Drinkwaterbesluit 2011)), the microbiological risks are negligible compared to the situation without cooling. A point that the study of Volpe *et al.* (2012) did not take into account is the fact that temperatures in the heat exchangers may be locally higher. Because the volume is relatively small no additional effects for consumers downstream of the system have to be expected, but it may be a cause of risk for maintenance.

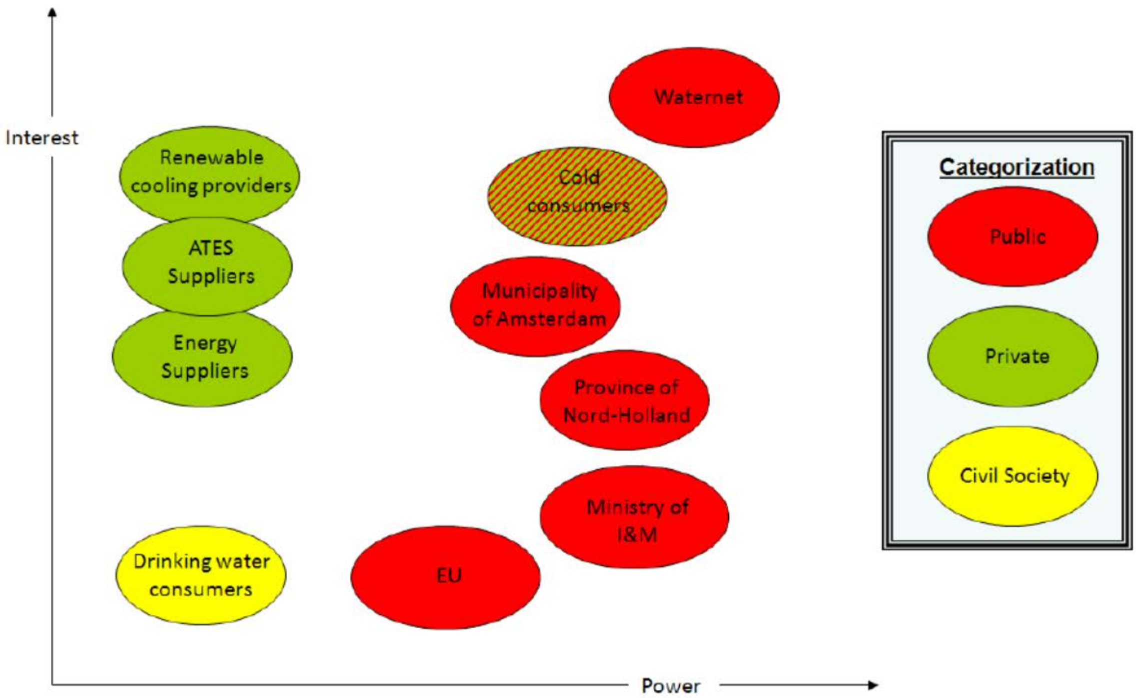

Figure 6.3. Power versus interest matrix of stakeholders.

A second water quality aspect investigated by (Volpe *et al.* 2012) was the increased metal solvency at higher temperatures. Their focus was primarily on lead. However the distribution network does not contain lead mains anymore, which means that lead solvency is not important. Nevertheless, lead pipes may still be in use in some home installation ('behind the water meter'), but the temperature in these pipes is determined by the temperature in the house or building.

The next step in the study was a market analysis and an analysis of potential end-users for cooling by drinking water/ATES. It was found that hospitals, and care and nursing homes, are important users of (conventional) cooling capacity. More than 80 % of the buildings in this category apply cooling systems to achieve stable temperatures in e.g. operating rooms and for medical equipment. Typical installed cooling capacity is approximately 80 kWh/m^2/y. Office buildings have a lower cooling demand, approximately 40 kWh/m^2/y, but because many office buildings are present in Amsterdam the total cooling capacity involved in this segment is high as well. The final category, buildings with some kind of societal function (museums, schools etc.) have on average a cooling demand that lies in between, 60 kWh/m^2/y, but the variation in this segment is high due to the many different functions of the buildings.

It was concluded that

1. The application of drinking water mains for cooling through ATES is technically and economically feasible, as long as certain conditions are met: ATES temperature 8-10 °C, unbalance in ATES > 4 TJ/y, distance between ATES and drinking water mains is short.

2. The public acceptance is mostly determined by the economic perspective: if a positive business case can be guaranteed, the acceptance will be high, because the willingness to use sustainable cooling is high.

3. Water quality risks are negligible if the drinking water temperature is kept below 25 °C.

4. There is a need for effective communication on societal benefits and risks of using drinking water for cooling supply

5. Contacts between Waternet and energy suppliers is necessary

Several case studies have been investigated to verify the general conclusions and investigate the specific aspects of these cases. The case studies were FOM/AMOLF (molecular and material science research center), Schiphol airport and an ICT Data Center. Due to the lack of exact data, the interpretation of the business cases in this stage is difficult. Only for the Schiphol case more exact figures are available.

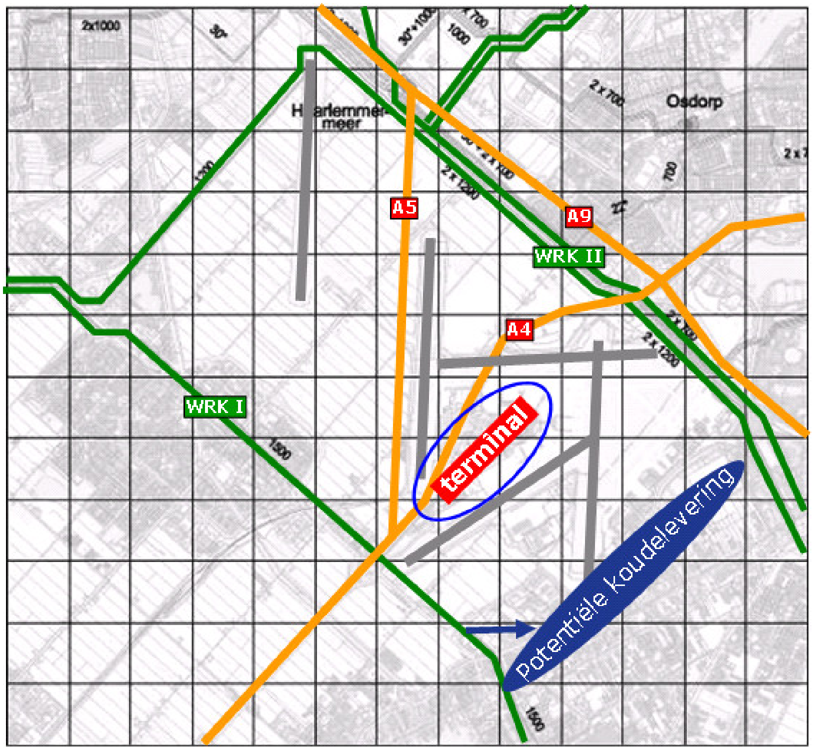

Figure 6.4. Transport mains for pretreated water around Schiphol airport.

6.2.3 Combining water and energy supply

Because water is used to store and supply thermal energy, the thought came up to combine the drinking water distribution system and a supply system for thermal energy in one distribution network (Brolsma *et al.* 2013). A conceptual framework was provided in this study and applied to the 19th century residential area Watergraafsmeer in Amsterdam. The concept combined a single drinking and thermal energy supply system with aquifer thermal energy storage. The energy savings in the Watergraafsmeer case study seemed to be very limited (only 7 %). The key factor was the seasonal performance of the required heat pumps. Moreover, the drinking water quality in a combined network cannot be guaranteed to meet the standards and additional point of use treatment is required. Due to the relatively low costs and high quality of the current drinking water system, a combined system was assumed to be not feasible.

6.3 Heat recovery from sewers

Energy consumption for preparing warm tap water is relatively high. In an average Dutch home (2.2 inhabitants), approximately 1,600 m^3 of natural gas is used for space heating (80 %) and warm tap water preparation (20 %). In Table 6.1 an overview is given of the drinking water consumption in The Netherlands, the temperatures of use and the required energy to reach this temperature. The total primary energy consumption for productions of warm water is 14,665 kJ per person per day. An average family therefore uses 11.8 $GJ_{primary}$/y to heat water. The laundry machine and dishwasher use electricity to heat the water, the other tap water is assumed to be heated by natural gas. After use, the warm water leaves the house via the sewer. In general, the water after use will have only a slightly lower temperature. The sewer system is therefore an important heat sink of a house. By recovering this heat and increase the temperature by a heat pump the thermal energy can effectively be reused.

Table 6.1. Average per capita water consumption (warm and cold) (Blokker et al. 2013) and the required primary energy for heating.

WATER USE	DESCRIPTION	AVERAGE VOLUME (L/CAP/D)	HEATED VOLUMEN (L)	PRIMARY ENERGY USE[1] (KJ/CAP/D)
Bath	Heated to approximately 40 °C	3.5	3.5	450
Bath room tap	Warm water for shaving; for brushing teeth and washing hands, cold water use is assumed	4.0	1.5	330
Dish washer	Heated to approximately 40 °C	2.1	2.1	610
Kitchen tap	Warm water for dish washing, cleaning and food preperation; cold water for hand washing and watering plants	14.8	7.0	2,335
Garden tap	Not heated	13.4	0	0
Shower	Heated to approximately 38°C	49.3	49.3	5,940
Toilet	Not heated	21.4	0	0
Laundry machine	Heated to 40–60°C. Final flushing with cold water	14.2	10.0	5,000
Total		122.7	73.4	14,665

[1] Energy consumption calculated assuming a drinking water temperature of 12 °C and a heating efficiency of 90 % for gas heating and 40 % for electrical heating (dish washer, laundry machine)

6.3.1 Business case James Wattstraat

In the Watergraafsmeer area of Amsterdam, Waternet has planned renovation of the sewage system in the James Wattstraat by 2015 (Tissier *et al.* 2011). This renovation offers the opportunity to place a waste water heat recovery (WWHR) system in the sewage system. This system can provide several nearby buildings with low temperature heat which can be used for spatial heating. As the system would use an integrated heat exchanger a robust system can be realised that causes no obstruction for flow. Because the system has to be renovated, the additional investment costs would be relatively low. The heat from the sewer will be used in an existing ATES system. In the business case it was estimated that the investment would be around € 460,000 and the CO_2 emission reduction would be around 360 ton CO_2 annually. The most important challenge in this project is on the organisational side. Several stakeholders have to be brought together. They have to provide new services that are currently not in their portfolio, while existing tasks, e.g. wastewater drainage, should remain at the existing quality level. An additional complicating factor is that Waternet is a public entity and energy supply is a private market. A solution may be to establish a so-called ESCO (Energy Service Company) (Mol et al, 2011). Communication is a key success factor in this project.

Research by Monsalve (2011) continued to identify other potential zones for heat recovery from sewers in Amsterdam. The study determined the minimal technical requirements for implementation: potential customers for the extracted heat should be available at a short distance from the abstraction point, the sewer should have a minimum flow of 10–12 L/s and a diameter of at least 400 mm (typically at the end of the (sub)system), and the sewage temperature should not be below 12 °C to have an efficient heat exchange and to prevent to have too low temperatures at the sewage treatment plant. With these criteria 14 zones were preselected for further investigation and 5 of them were studied further in detail. The zones with the highest flow rates have the highest potential for heat recovery.

6.3.2 Available heat in the sewer system

In 2012 a study has been conducted to determine the heat available in a small sewer system and a model is developed to describe dynamics of the heat available in the sewer system (Hofman *et al.* 2014). The system consists of two sewer pipes connected to a pumping station in the middle. Connected are about 140 dwellings. During several weeks water flows temperatures inside an isolated sewer system in the North part of Amsterdam were monitored. Temperature monitoring was done using Distributed Temperature Sensing. This method uses an optical fibre cable to detect temperature. A temperature profile (spatial resolution 1 m) for the whole length of the cable can be measured and stored at high frequency (every 30 seconds). In this way the dynamic variations of the sewage can be determined. In Figure 6.5 an example is given of such a measurement. The horizontal axis represents time, in total 24 hours.

In Figure 6.6 the temperature near the pumping station, the flow rate and the calculated available heat is shown. In the first place a highly dynamic behaviour is observed, due to many individual discharges. Furthermore a strong diurnal pattern is clearly recognisable.

The average flow at the pumping station is 0.25 L/s. If a drinking water consumption of 130 L/cap/d is assumed, this flow equivalent to 166 inhabitants (1.16 persons per address). On average this system can provide 4.8 kW heat (150 GJ/y). As an average household in the Netherlands (2.2 persons) uses approximately 1,600 m^3 natural gas (72 GJ/y) for spatial heating and warm tapwater, it can be calculated that in this system sufficient heat is available to supply heat to approximately 4 dwellings (if a cooling of the sewage to 12 °C is assumed).

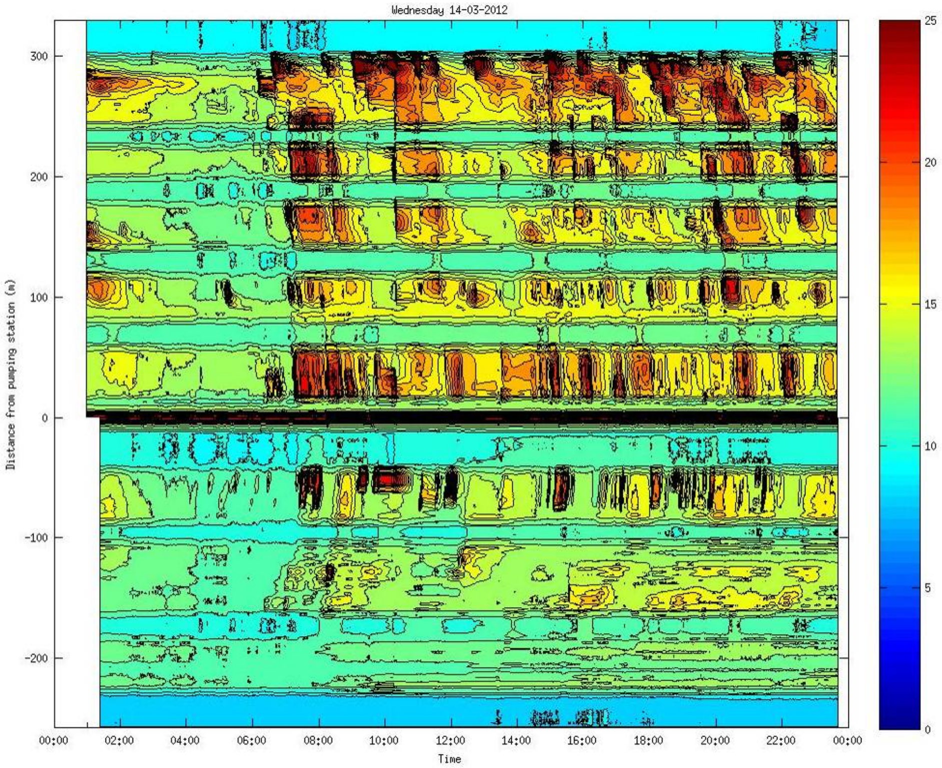

Figure 6.5. Dynamic temperature profile in a small sewer system monitored for 24 hours.

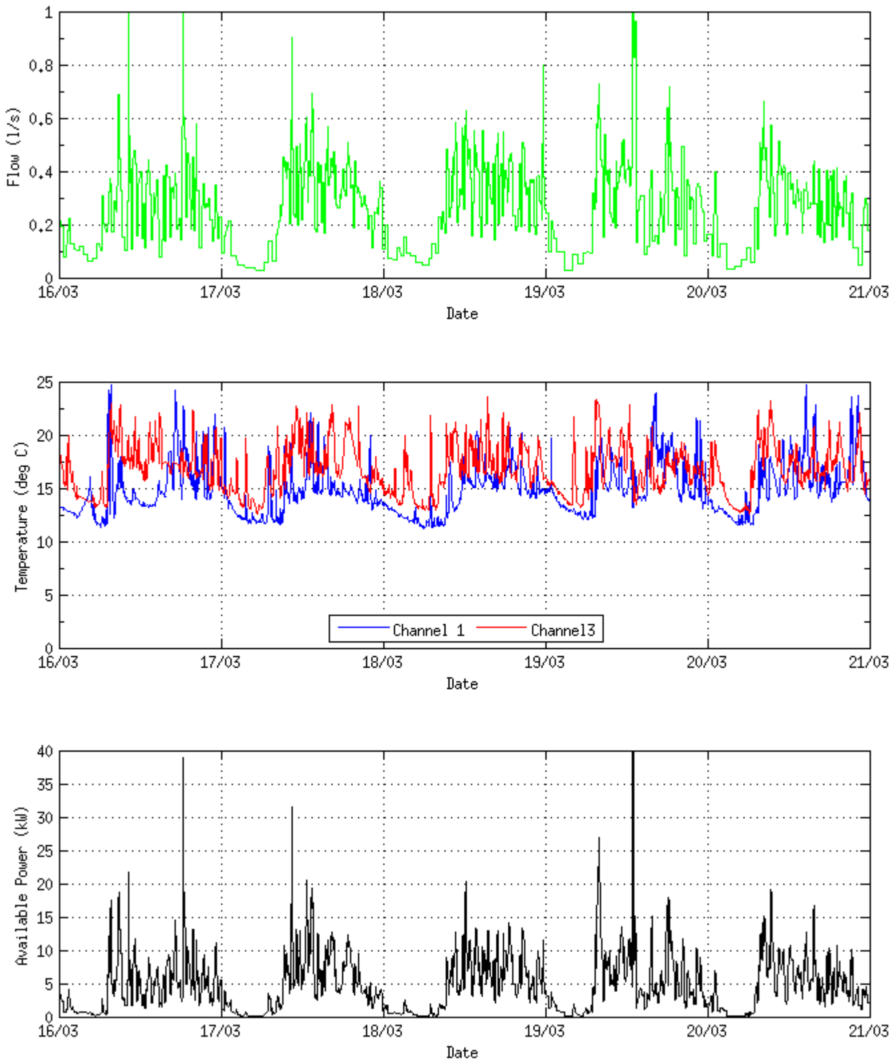

Figure 6.6. Flow (top), temperature near the pumping station (middle) and available heat (bottom). (Reference temperature 12 °C).

If the average consumption of warm tap water in Figure 6.6 is assumed and a reference temperature of 12 °C of cold tap water is assumed, it can be calculated that 3.9 GJ is required per person to prepare warm tap water (heating efficiency 90 %). With the assumption of 1.16 person per dwelling in the study area a total energy consumption of 650 GJ/y is used. This means that approximately 30 % of this heat can be recovered at the pumping station.

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7. ENERGY OPTIMISATION AT SCHIPHOL AIRPORT WASTEWATER TREATMENT PLANT

7.1 Introduction

Large potentials exist in energy saving and generation in the water system. Examples of technology implementation at the water industry are available. New concepts and technology improvements are needed that view water as a carrier of thermal and organic energy. Examples of energy efficiency and heat and power generation from wastewater are:

- Increased carbon concentration directed for maximised biogas production and therefore lower aeration requirements in the waterline

- Enhanced biogas production, by optimization of the sludge treatment or digester operation

- Side stream treatment for N-removal, eventually combined with nutrient recovery

Water, energy and nutrient flows have to be considered together rather than separately and have to be designed with flexibility for future changes. These flows interact, therefore the water sector should interact with other sectors to discuss common challenges and develop shared solutions. Specific cases can serve as good example for energy optimization. Here the Amsterdam Airport Schiphol wastewater treatment plant (WWTP) case will be described.

7.2 Schiphol Airport

7.2.1 Schiphol watercycle

Currently there are annually about 50 million passengers passing Amsterdam Airport Schiphol and approximately 60,000 FTE employees are working at the airport. In total, 1.223 million m3/y of drinking water is used. There are 1,000 toilets, of which 900 public toilets, and 450 urinals, of which 400 public urinals, including 263 water free urinals. Furthermore, the airport has more than 1,300 hotel rooms available. From the vacuum toilets of the airplanes another 21,000 m3/y of concentrated wastewater is created.

The ambition of Schiphol is to become a climate resistant and carbon neutral airport. Water is of major importance in achieving this ambition and the idea is to show the benefits of making water and energy leading in urban planning. Particularly of concern is the energy-water nexus which is why the generation of energy from wastewater is one specific goal to be achieved as well as energy efficient wastewater treatment. In total, 1.5 million m3/y wastewater is treated at the WWTP of Schiphol airport. The watercycle of Schiphol is comparable to a city with 45,000 inhabitants.

7.2.2 Schiphol WWTP

The WWTP of Schiphol is in use since 1965 and the assets are owned and operated by Evides Industriewater since 2004. Daily approximately 4,000 m3 of wastewater is treated in a biological process. The process consists of a selector, activated sludge plant with successively an anaerobic, anoxic and aerobic zone and settling tanks (Figure 1). Surplus sludge is digested. A primary settler is not in use, because of the low BOD:N-ratio of the wastewater. Wastewater influent characteristics and the obtained removal efficiencies are given in Table 7.1 (data from 2011). Besides biological phosphorus (P) removal, iron sulphate ($Fe_2(SO_4)_3$) is dosed before the final settling tank for sufficient P-removal. Every year approximately 1,800 ton of sludge with a dry solid content of about 23% is disposed of. The average effluent temperature is 18.6°C, while the digester is operated at 32°C, producing 125,934 m3 of biogas per year. Together with an additional 3,653 m3 of natural gas, this is enough for heating the digester and buildings. All electricity is obtained from the grid (2,146,663 kWh/year).

Table 7.1. Schiphol wastewater influent characteristics and removal efficiencies.

CHARACTERISTIC	AMOUNT (mg/L)	REMOVAL EFFICIENCY (%)
COD	850	96
BOD	386	99
N	131	88
P	19	93

7.2.3 Schiphol WWTP energy optimization options

This chapter describes the following topics.

First an overview was made of the current energy use and energy flows in the Schiphol watercycle.

Next the following energy optimization options for the WWTP Schiphol were considered:

- Side stream nitrogen removal
- Phosphorus recovery from centrate and fecal deposits from airplanes
- Enhanced energy production from combined digestion of sludge and fecal deposits from airplanes

Finally total concepts are discussed and future technologies for upgrading the current WWTP with an emphasis on organic carbon concentration for maximizing digestion. Options to be investigated include AB-system, possibly with dynamic filtration, and with additional cold Anammox (ANaerobic AMMonium OXidation) (Hellinga et al., 1998).

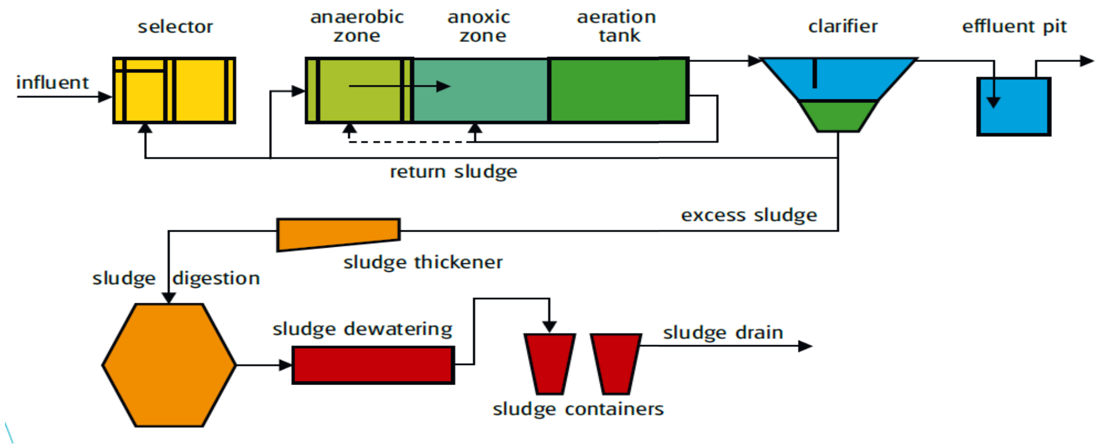

Figure 7.1: Schematic overview of the Schiphol WWTP

(http://www.evides.nl/en/Industrial/References/Pages/AWZISchiphol.aspx)

7.3 Energy in the Schiphol watercycle

Data of the year 2011 about energy in the watercycle of Schiphol was retrieved (Table 7.2) and some assumptions, as in earlier studies, were used, like the average water temperature of drinking water at arrival (10°C), average temperature of drinking water when used (27°C), the potential heat exchangers efficiency (50%) and the average values for energy use per m^3 of water for drinking water production and distribution by Waternet (0.41 kWh/m^3) and sewage transport (0.11 kWh/m^3).

Table 7.2. Collected data for an overview of energy use in the watercycle of Schiphol

ITEM	UNIT	AMOUNT
Number of passengers		50,000,000
Purchased drinking water	m^3/year	1,223,461
Intrusion of rainwater and groundwater into the sewer	m^3/year	277,000
WWTP influent	m^3/year	1,500,000
COD in WWTP influent	ton/year	1,275
Extra C-source for the WWTP	kg/year	146,000
Electricity purchased for the WWTP	kWh/year	2,146,663
Electricity used for aeration of WWTP	kWh/day	2,500
Natural gas purchased for the WWTP	m^3/year	3,653
Own produced biogas at the WWTP	m^3/year	125,934
Average temperature in the digester	°C	32
Average effluent temperature	°C	18.6

The data was used to calculate and compose an overview of the energy use in the watercycle of Schiphol (Figure 7.2). It is very obvious that the energy use for heating water is huge compared to the energy use for other aspects, e.g. water treatment, in the watercycle. This also implies that heat recovery can result in substantial energy use reductions. Furthermore, the energy consumption for wastewater treatment is much more than the energy used for drinking water production, drinking water distribution and sewage transport.

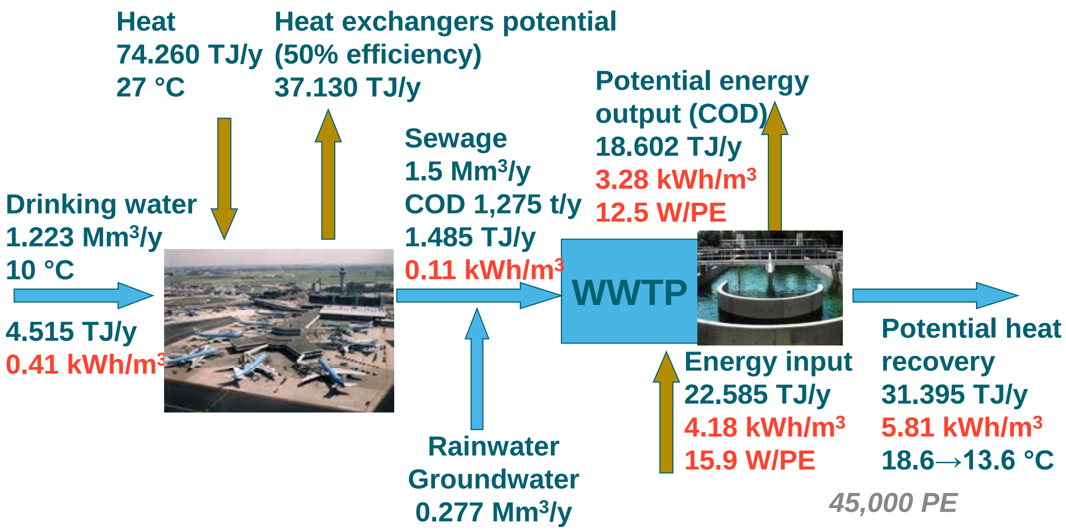

Figure 7.2. Overview of energy in the watercycle of Schiphol

On average every day 5.881 kWh of electricity is used for the total Schiphol WWTP. Of this amount 2.500 kWh per day is used for aeration of the wastewater in the activated sludge tanks. In comparison to the average Dutch municipal sewage treatment plant the WWTP of Schiphol uses more energy per cubic meter of treated wastewater, but the load of the Schiphol WWTP is also higher. Nevertheless, also the amount of electricity used per kg $BOD_{removed}$ is higher for the Schiphol WWTP. This could be caused, among other things, by the size of the Schiphol WWTP (economy of scale) and the applied ceramic aeration elements for treatment of the Schiphol wastewater. The ceramic aeration elements are always on and not controlled by the NH_4/NO_3 concentrations. Aeration management could probably be optimized for more energy efficient wastewater treatment.

Because of the low BOD:N-ratio of the wastewater there is no primary settler in use. On the contrary, an extra external carbon source (deicing liquid, glycol) is provided to the wastewater for denitrification in the WWTP main stream. However, the extra carbon is not only used for denitrification and causes a higher oxygen demand, with associated higher energy requirements for aeration.

7.4 Nitrogen removal in side stream

An interesting solution to limit the N-load to the WWTP mainstream is removal of nitrogen from the digested sludge dewatered centrate, the so called side stream. The filtrate is normally still a bit warm from the higher digester temperature compared to the influent and has a relative high concentration of nitrogen and a low concentration of carbon. This facilitates autotrophic N-removal by the Anammox-process (ANaerobic AMMonium OXidation)(Hellinga et al., 1998). In the Anammox-process, nitrite and ammonia are converted into nitrogen gas without external carbon source (autotrophic) under anaerobic conditions. Therefore, more carbon can be used for energy production via digestion and less energy is used for aeration, since ammonia is only partly converted to nitrite by ammonium oxidation in an aerobic process.

At Schiphol there is on average 35 m^3 centrate per day, with an N load of 38 kg. Treating this stream separately saves 8% in aeration in the main stream. Including energy requirement for side stream treatment (1.0 kWh/kgN) (Stowa 2008-18), the overall energy reduction by application of side stream N-removal in the current set-up is approximately 58 MWh/year, equivalent to 2.7% of total electricity consumption. When fecal deposit is directly send to the digester, instead of mixed in the influent, the N-load of the centrate increases to 148 kg per day. This reduces the needed aeration in the main stream with 31% and the overall energy requirement with more than 230 MWh/year (including energy requirement for side stream treatment), equivalent to 11% of total electricity consumption.

7.5 Phosphorus recovery

Phosphorus is a finite resource and an essential element for growth. Conventional methods remove phosphorus from the wastewater by precipitation with metals or by biological accumulation in cells (enhanced biological phosphorus removal). In both methods phosphorus is removed in the excess sludge and in most cases not available for reuse, especially in countries where all sludge from WWTPs is incinerated such as in the Netherlands.

Technologies for phosphorus recovery focus on precipitation of phosphate from concentrated streams producing a phosphorus precipitate which can be used as a fertilizer. The following options for (indirect) energy savings are possible when applying phosphorus recovery:

- Saving in use of chemicals as no iron is needed for conventional phosphorus removal
- Saving in production of artificial fertilizer from phosphorus rock
- Saving in sludge handling due to less sludge production (dewatering and incineration)

The phosphorus balance for the WWTP at Schiphol is shown in Figure 7.3. Three streams are suitable for phosphorus recovery, containing high concentrations of ortho phosphate: surplus sludge, centrate from digested sludge and fecal deposit streams from airplanes.

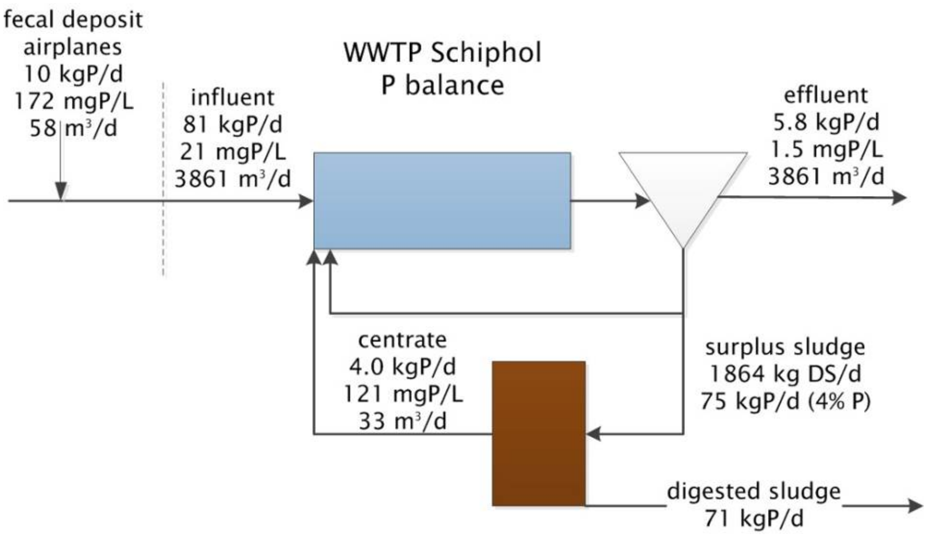

Figure 7.3: Phosphorus balance at WWTP Schiphol

Struvite recovery from the centrate and fecal deposit stream results in a struvite production of 11 kg P per day (assuming 75% efficiency). This amount of phosphorus does not need to be removed by conventional precipitation with iron and electricity consumption for conventional P-fertilizer production is avoided, saving 57 MJ/kg P, which is equivalent to 2.8% of the total electricity consumption of Amsterdam Airport Schiphol WWTP in 2012.

Table 7.3. Energy requirements for phosphorus removal using different technologies (Maurer et al., 2003); includes running energy consumption (electricity, fuel and chemicals)

Energy requirement chemical P removal with iron	49	MJ/kgP
Energy requirement biological P removal	28	MJ/kgP
Struvite production for P removal	21	MJ/kgP
Average P-fertiliser production	29	MJ/kgP

In the future the chemical P removal with iron can be fully avoided by applying biological P removal in the main stream and subsequently P removal by struvite precipitation after digestion at the WWTP of Amsterdam Airport Schiphol. Including the energy avoided for fertilizer production, biological P removal combined with struvite precipitation requires less energy. Life cycle assessment of such scheme was done by Waternet and resulted in the same conclusions (De Danschutter et al., 2011).

Struvite production at the WWTP offers also possibilities for treatment of other concentrated phosphorus streams like urine or black water. Current infrastructure is not suitable for urine collection, but when terminals are upgraded or new terminals are built, urine collection offers several advantages like increased struvite production, reduced aeration in the main stream WWTP process and accessory savings in energy requirements.

7.6 Separate treatment of fecal deposit from airplanes for energy recovery

The fecal deposit originating from vacuum toilets in airplanes is currently mixed with wastewater from terminals and other buildings at Schiphol. Due to the use of vacuum toilets this fecal deposit is a concentrated stream with a composition comparable to the so-called 'black water' (Kujawa-Roeleveld and Zeeman, 2006) (de Graaff, 2010) (Table 7.4).

Table 7.4. Composition of fecal deposit stream from airplanes at Schiphol and loads compared to total wastewater stream (total load yearly average values from 2012; fecal deposit stream average value of 10 samples in 2013)

	UNITS	FECAL DEPOSIT STREAM	WWTP INFLUENT	LOAD FECAL DEPOSIT (KG/D)	TOTAL LOAD WWTP (KG/D)	%
Q	m^3/d	58	3.861	-	-	-
BOD	mg/L	2500	386	145	1490	10%
COD	mg/L	10400	860	603	3320	18%
P total	mg/L	180	21	10	81	13%
P ortho	mg/L	136	-	7,9	-	-
NKj-N	mg/L	1900	131	110	506	22%
NH4-N	mg/L	1575	-	91	-	-
SS	mg/L	4150	-	241	-	-
Mg	mg/L	5	-	0,29	-	-

Concentrated black water can be used for recovery of phosphorus and energy. Possibilities for phosphorus recovery and related energy savings are described in the previous section.

Conventional treatment at the current Amsterdam Airport Schiphol WWTP of the total load of COD results in a biogas production of 17% COD equivalent (125,934 m^3 biogas/year, Table 2). This means that 17% of incoming COD is recovered in the form of methane. When the fecal deposit stream is anaerobically digested instead of mixed with other wastewater and treated aerobically, this will result in a biogas production of 27% COD equivalent. Overall the methane potential of 136 m^3 CH_4/d is equivalent to 167 MWh/year which is 2.9% of total electricity consumption. The calculations are shown in table 7.5 and 7.6.

Table 7.5. Calculations for energy production by co-digestion of fecal deposit at Schiphol WWTP

Methane potential	362	kg CH_4-COD/d		
Methane amount	136	m^3 CH_4/d		
Energy potential	4840	MJ/d		
Electricity	1646	MJ/d	167	MWh/year
Heat	2468	MJ/d		

Principles: 60% anaerobic biodegradability on COD basis (Kujawa-Roeleveld and Zeeman, 2006, de Graaff, 2010); 4 gCOD/gCH_4; density 0.67 kg/m^3 CH_4; assumption methane content in biogas 60%; 35.6 MJ/m^3 CH_4; assumption efficiency Combined Heat and Power engine 85% of which 40% electricity and 60% heat; 1 kWh = 3.6 MJ

Other effects of the diversion of the fecal deposit stream directly to the digester is a reduction in COD load in the activated sludge system (18%) and therefore a reduction in needed aeration, but also in excess sludge production from the main stream for digestion. Nitrogen in fecal deposit can be removed in subsequent side stream autotrophic nitrogen removal (see section about N removal in side stream).

Unknown is the effect on anaerobic digestion of Turco Biofresh DD which is used as deodorant and disinfectant in the airplanes toilets of certain airline(s). Currently there are no negative effects when the fecal deposit stream is mixed and biological treated with the other wastewater stream. The effects of Turco biofresh DD on anaerobic digestion of the concentrated fecal deposit stream need to be investigated.

Table 7.6. Calculations to compare electricity production with total electricity use and COD recovery

Electricity use WWTP Schiphol:	2,147	MWh/jaar
	5,882	kWh/d
Current biogas production:	12,5934	Nm^3/jaar
	345	m^3/d
	207	m^3 CH_4/d
	551	kg CH_4 COD/d
Current energy recovery:	17%	of COD influent load is recovered as methane
Potentially to be increased to:	27%	of current COD influent load to be recovered as methane when fecal deposits are directly co-digested

7.7 Summary, discussion and conclusions

Figure 7.4 show the loads of the Amsterdam Airport Schiphol WWTP in the current situation. In Figure 7.5 the loads of the possible concept with diversion of the fecal deposit stream directly to the digester, including autotrophic N-removal and struvite precipitation. The possible savings in energy consumption are also shown.

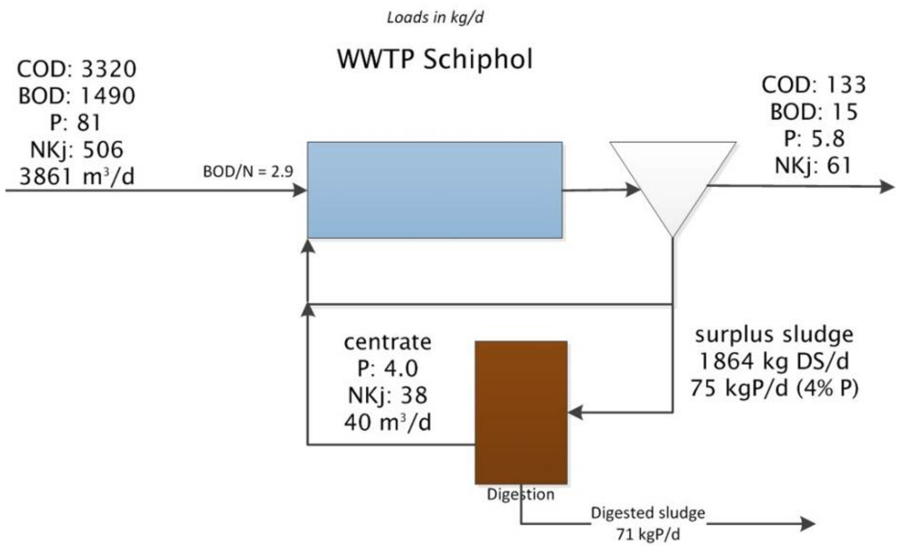

Figure 7.4. Loads in current Amsterdam Airport Schiphol WWTP scheme

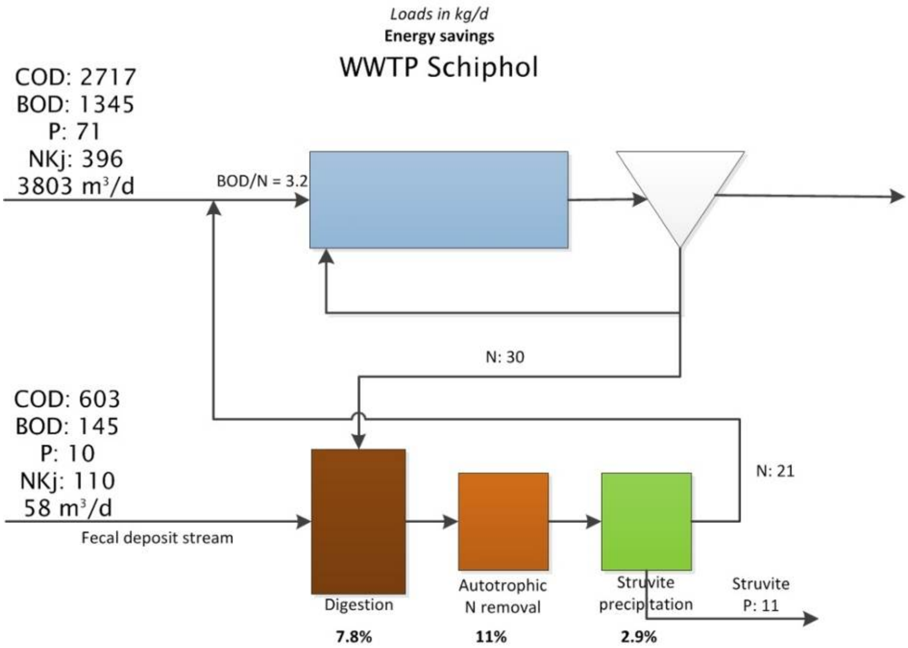

Figure 7.5. Loads [kg/d] when fecal deposit stream is treated separately: co-digestion with excess sludge and subsequent autotrophic N removal and struvite precipitation

Separate treatment of the fecal deposit stream and side stream autotrophic nitrogen removal will improve the BOD/N ratio in the influent stream to the main stream activated sludge system from 2.9 in the current situation to 3.2 in the load minus fecal deposit stream (assuming 85% N removal).

The improvement in BOD/N ratio will result in a lower demand for external carbon source for denitrification. Currently 158,000 kg/year of external carbon source (deicing liquid, glycol) is used. This carbon source has an indirect energy use of 26.5 MJ/kg (GER-value of glycol, gross energy requirement).

Another concept with emphasis on COD concentration for maximizing digestion is the A-stage process. This is a high loaded activated sludge system without primary sedimentation in which sludge production is maximized and conversion of COD to CO_2 is minimized. Existing WWTPs with A-stage already achieve a 50% COD recovery in the excess sludge, which can be directed to the digester (De Graaff et al., 2013). Currently the A-stage processes are further investigated to design guidelines for maximum carbon recovery; a maximum of 70% COD recovery in excess sludge seems to be feasible. When this excess sludge is digested, this will significantly increase the biogas production. Nitrogen from the effluent of the A-stage can be removed by autotrophic nitrogen removal, even at low concentrations and low temperatures (“cold Anammox”). This is currently under investigation. However, applying A-stage does have consequences for the way of phosphorus recovery. Biological phosphorus removal in the main stream and A-stage cannot be implemented in one process. Therefore this concept reduces the total recoverable phosphorus, but reduces the energy requirements of the Amsterdam Airport Schiphol WWTP.

The savings in electricity consumption require adaptation of the existing infrastructure. Sidestream nitrogen removal based on current situation, treating only the centrate stream, is easily integrated. Sidestream nitrogen removal furthermore contributes to the need of removing more nitrogen and achieving lower effluent concentrations. Separate collection and transport of fecal deposit streams and other streams requires significant changes in existing infrastructure. Regarding the current distance and route (fecal deposit stream is mixed with other wastewater at the airport and from there transported to the WWTP) either a separate pipe has to be constructed or the fecal deposit streams has to be transported by truck. Implementing the A-stage process and Anammox requires an intermediate settler and changes in operation.

Several aspects need further research:

- High current electricity consumption of the WWTP compared to average electricity consumption at Dutch WWTPs
- Co-digestion of fecal deposit and the effect of the deodorant and disinfectant used in the aviation vacuum toilets
- Application of biological phosphorus removal in main stream or application of A-stage and cold Anammox in the main stream
- Estimations of energy savings now include only running energy consumption (electricity, fuel and chemicals); a full business case has to be made to be able to make decisions on investments.
- Costs and the integration in existing infrastructure

7.8 References

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8. INTEGRATING PRESSURE AND ENERGY MANAGEMENT AND MICROGENERATION IN LANGHIRANO

8.1 Introduction

The objective of this task has been to develop a methodology for integrating pressure and energy management in Water Distribution Systems, with the aim to save both water and energy resources.

Three major actions can be identified in order to lead towards the above mentioned target:

1) Improvement of pump efficiency (optimizing the operating conditions and/or through devices like inverter and soft start)

2) Assessment of leakage reduction effects on energy saving (by pressure management or pro-active detection techniques).

3) Energy recover/generation by replacing PRVs with turbines or installing reversible pumps (Pumps As Turbines – PAT).

The Water System of Langhirano, hereinafter described, appears as a meaningful case study for the water/energy nexus under several different perspectives: the system is almost completely supplied by pumps (high energy impact) and the most densely populated part of the network is already sectorized and organized in seven District Metered Areas (DMAs).

The research will then focus on the presence of pressure reducing valves at the entrance of each district, investigating how to recover energy from the existing pressure excess at the same valves.

This will be done by integrating two main actions:

- Development of a numerical tool (accounting for the specific machine efficiency) in order to search for the optimal turbine/PAT to be installed in a certain point, leading to the highest amount of energy produced, given the flow and head patterns during the day (Point 3 mentioned above)

- Assessment of the energy producibility under different operating scenarios of the water distribution system, considering both PRV settings (Point 2) and pumps' operation (Point 1)

Among others Genetic Algorithms are used to identify the optimal DMA boundaries and to determine the optimal type, location and setting of the PRVs (based on Awad et al., 2010).

Quantitative information regarding water and energy saving (with respect to the present conditions) will be provided for all considered scenarios.

8.2 Methods

As previously introduced, the activities aim at an overall resource saving (water and energy) plus at taking advantage of existing dissipated energy to be recovered.

In a WDS, the latter is well explained by the following flow chart.

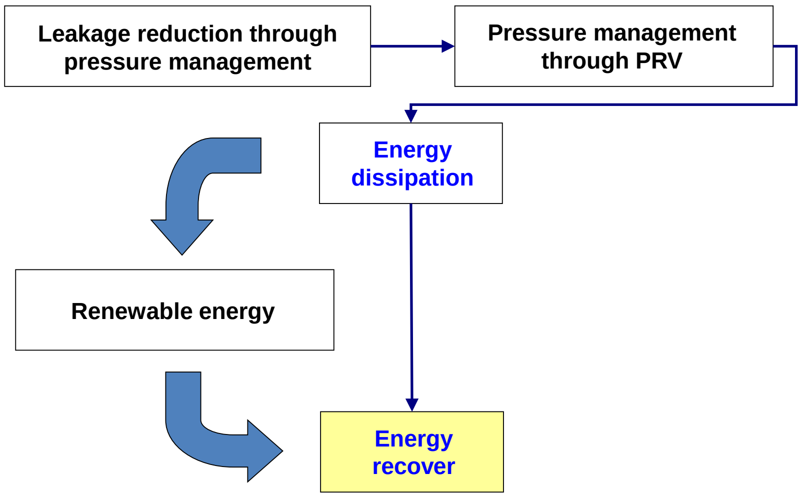


Figure 8.1. Energy recovery at Pressure Reducing Valves in a Water Distribution system

Given the technical characteristics involved and the ranges of flow and head available, Francis turbines appear as the most suitable for the energy recover / microgeneration purpose.

The following figures present s a possible installation scheme for a microturbine in an existing chamber where a Pressure Reducing Valve is already hosted.

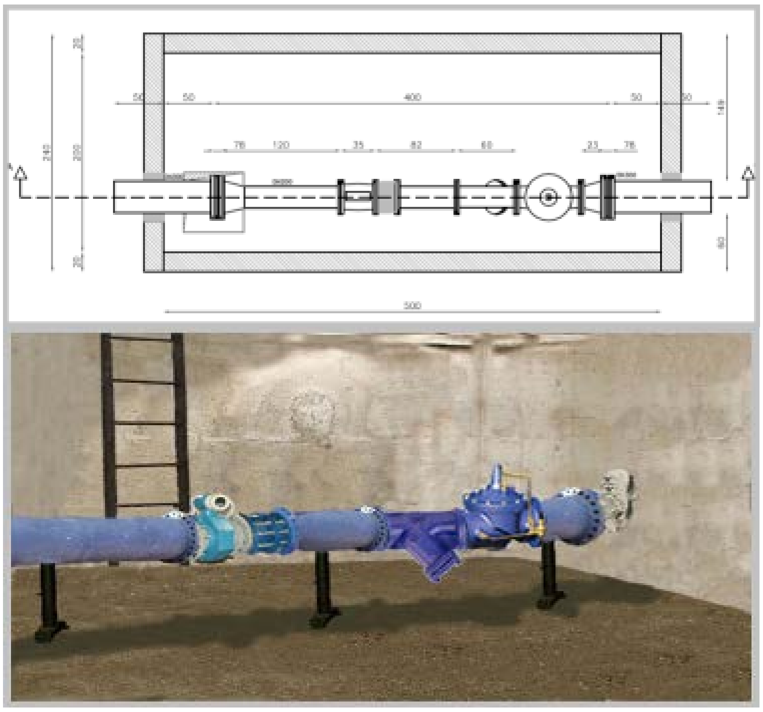


Figure 8.2. Example of chamber hosting a PRV

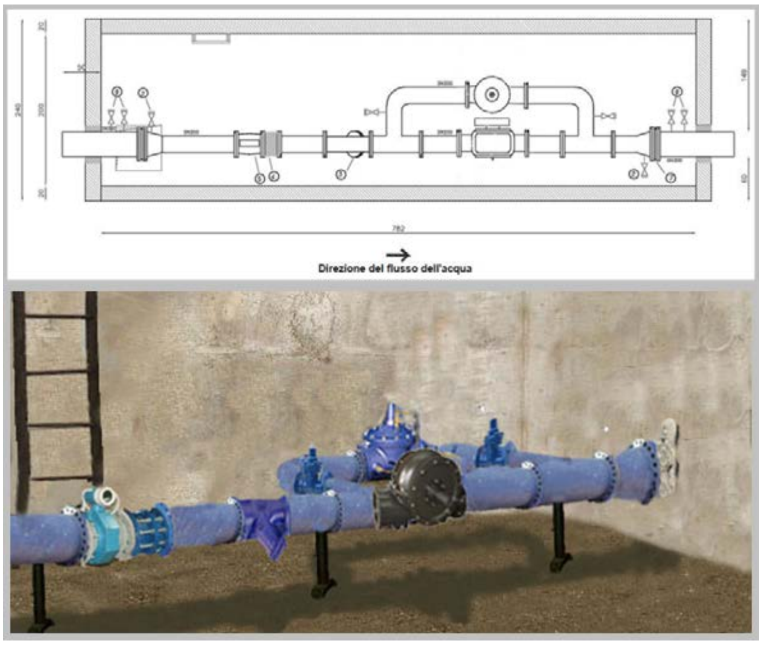


Figure 8.3. Example of chamber hosting a PRV, where a microturbine is installed

8.2.1 Analytical model

The basic parameters involved in the operation of a generic hydraulic turbine are:

- Hu = net available head;
- Q = flow;
- n = rotation speed;
- ηt = total efficiency

The above four values allow for calculating the effective power and the momentum of the turbine. The turbine performances are generally determined through experimental measurements and presented in a (n, Q) chart, called hill diagram, where Hu is kept fixed.

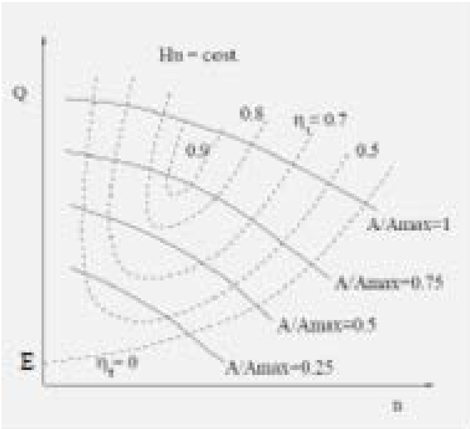


Figure 8.4. Hill diagram for a hydraulic turbine

The diagram shows the flow curves with degree of opening of the distributor valve (Aptd) constant as a function of n, for a fixed value Hu. Furthermore, each pair (n, Q) corresponds to a value of ηt, for which it is possible to join the points with ηt = constant in order to obtain a second family of curves. The curve ηt = 0 identifies the set of points of operation in which the mechanical efficiency is zero.

In the hill diagram for Francis turbines (selected for this application), the lines at an equal degree of openness (Aptd = constant) are not horizontal but show an increasing or decreasing trend, since the flow rate through the is influenced by the speed of rotation of the impeller.

The possibilities of adjustment of the system are given by the degree of opening of the distributor of the turbine (APDT) and by the flow rate will be diverted into the valve (Qv).

In practice, if the turbine is forced to operating conditions beyond its capabilities, the flow through the valve should be reduced and diverted through a bypass in order to ensure the passage of the flow rate required by users (Qu).

A function F exists, capable of describing the operation of the machine:

$$Qt = F(\eta t, Apdt, n) \quad (1)$$

Keeping n fixed:

$$Qt = f(\eta t, Apdt) \quad (2)$$

Which can be inverted and turned into a new f2 function::

$$Apdt = f2(\eta t, Qt) \quad (3)$$

With this function, obtained by interpolating the hill diagrams, we can find the value of the degree of opening needed by the turbine. Should this be out of the operating capabilities then only the nominal turbine flow will pass through the machine and the rest will pass through the bypass. Once the flow rate through the turbine, the degree of opening of the distributor and the available head are known, the instantaneous efficiency and power generated can be derived, together with the energy that the system can produce.

The scheme represented in the simulation tool is shown in the following figure, including the variables hereinafter listed:

- Qu = flow to users
- Qt = flow through the turbine
- Qv = flow through the PRV
- H1 = upstream pressure
- H2 = downstream pressure
- H = net available head
- Apdt = opening of the distributor
- Ap VRP = opening of the valve

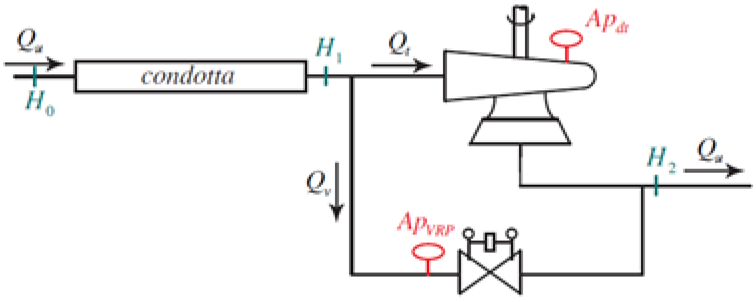


Figure 8.5. Turbine and PRV valve system

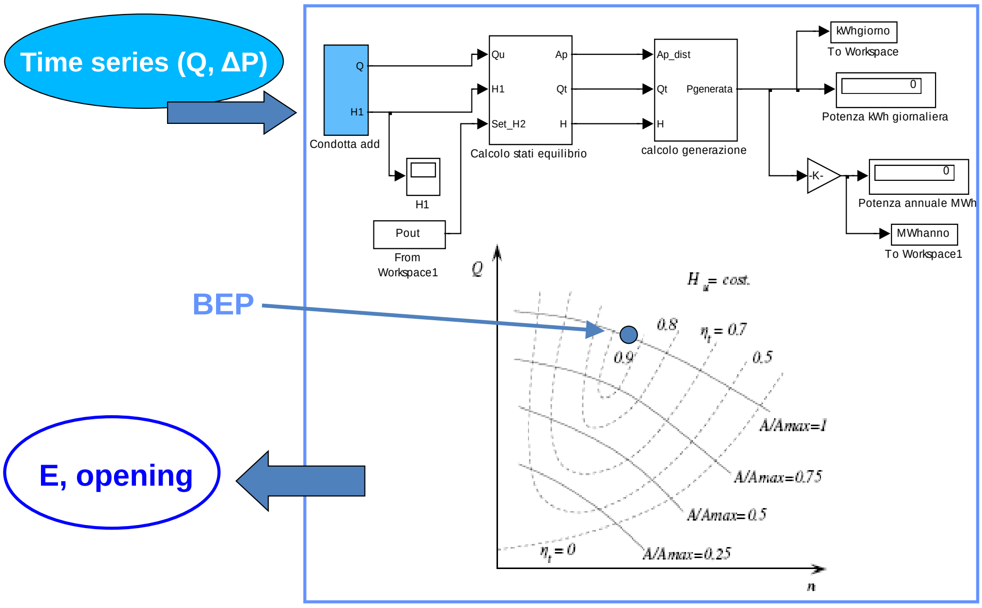


Figure 8.6. Overall schematic of the turbine modeling tool

8.2.2 Analysis of the energy produced

The conceptual model descrive above can be applied to any destre timeseries (daily time series in the present work).

Two are the time series required: flow through the existing valve and net available head as a difference between the pressure time series upstream and downstream the existing PRV valve.

The time series are then simulated introducing a turbine, which is defined by a pair of values (flow - Qp; net available head - Hp) representing the Best Efficiency Point (BEP) for that specific turbine. Therefore each pair of (Qp; Hp) represents a specific turbine, from which a certain amount of Energy can be produced, when working in the conditions defined by the previously mentioned time series. Assigning a produced energy value (Z) to each pair (X, Y), the energy retrievable by installing turbines with different BEP in a certain point, can be represented by a 3D surface.

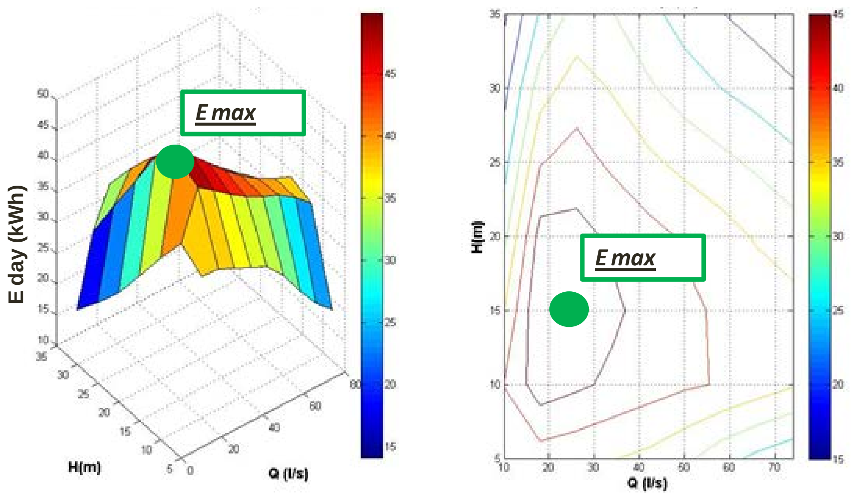


Figure 8.7. 3D charts representing the daily energy production for turbines with different BEPs

8.3 Langhirano case study

8.3.1 Water Distribution System of Langhirano

Water Distribution System of Langhirano is a completely independent system, in which there is only one point of transfer of water to a neighbouring network, with a total length of pipeline equal to about 222 km. It serves a population of circa 10,000 inhabitants, on a surface of 70.8 Km^2 and is located in the Northem part of Italy (Figure 8.1). The system retrieves water either from springs located in the higher portion of the municipal territory or from wells in the lower part, where the latter act as the major source. Only 68.5% of the system input volume is subject to disinfection. The Non Revenue Water is about 35% of the system input volume.

An overview of the system is shown in Figure 8. 2. The most densely populated part of the system has been organized in seven Pressure Management Areas (PMAs) (Figure 8.4), whose inlets are controlled by fixed setting pressure reducing valves (PRVs). The current status of PRVs is shown in Table 8.2, where the setting is related to the pressure that the valve has to maintain in the downstream node. The operation of some well pumps is controlled by a Supervisory Control And Data Acquisition system, in other cases the well pumps work with a timer control; only Joker well has a variable-speed pump. The storage volume is ensured by the three main tanks of Olive, Monterosso and Peroni (Table 8.1), whose level and flow are measured and transmitted to SCADA system.

The WDS of Langhirano appears as a meaningful case study for the water/energy nexus under different perspectives. The objective has been the application of a methodology for integrating pressure and energy management, with the aim to save both water and energy resources.

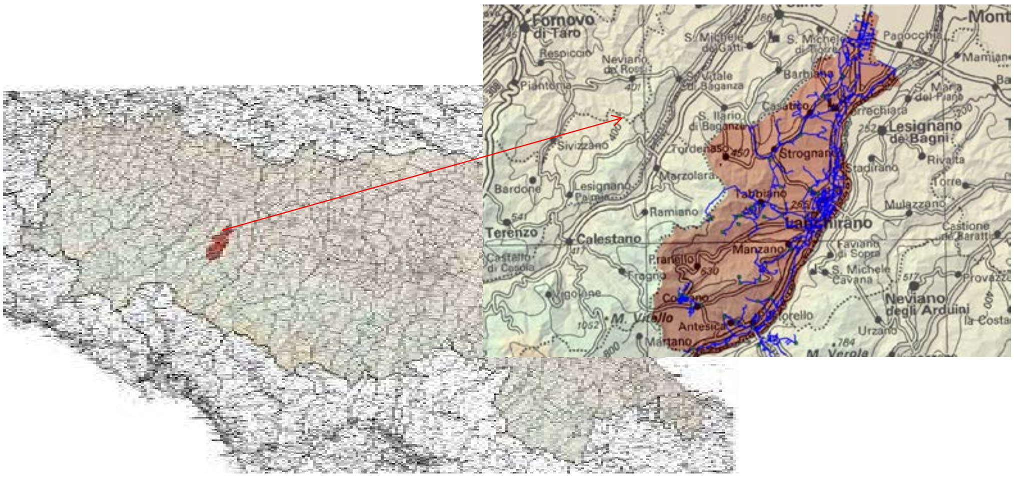


Figure 8.8. Territorial overview of the WDS of Langhirano

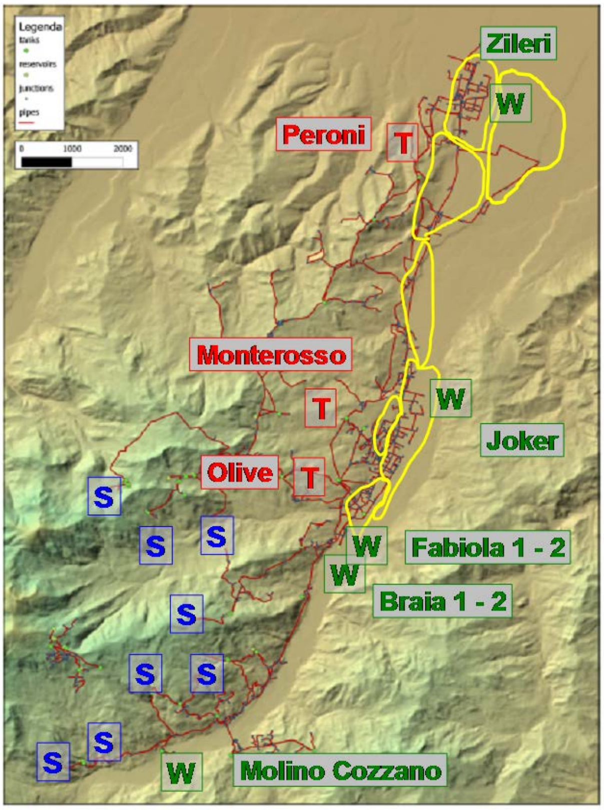


Figure 8.9. WDS of Langhirano: available water resources S (spring), W (well); T (main tanks); boundaries of PMAs indicated with the yellow line

8.3.2 WDS model

The implementation of the WDS model has required a skeletonization process, to pass from a detailed graph of the network, to a model coherent with the purpose of the analysis. It is possible to identify three phases (Figure 8.3):

Phase 1: Accurate demand assignment (semi-automatic geo referencing of yearly averaged user consumption) and tentative distribution of leakages (aimed at reproducing the 35% value declared by IAG).

Phase 2: Considerable reduction of nodes and pipes. The portion of the WDS with highest elevation is scarcely monitored and supplies a small part of the population. This part was cut off and replaced by single demand nodes (mostly fed by pumps), whose average value and pattern is coherent with the full network version.

Phase 3: Further reduction of pipes and nodes (skeletonized network). Pruning has been made turning pseudo-nodes into vertices. Pseudo-nodes have been determined according to the following criteria: nodes (with base demand = 0), linking just 2 conduits, whose diameters are identical and whose status are identical.

The above implementation leads to an acceptable 24h model. In Table 8.1 shows the main characteristics of the main tanks (Olive, Monterosso and Peroni) present in WDS of Langhirano; the availability of online measurements is also indicated. Online monitoring is related to the SCADA system, which extracted data have a time step of 5 min and to additional dedicated flow measurements, that IAG did to integrate SCADA information, using the same time step.

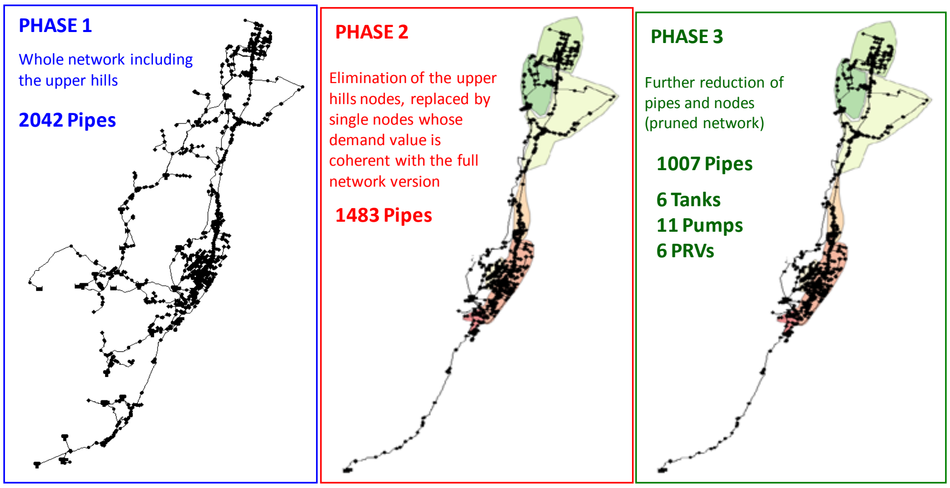
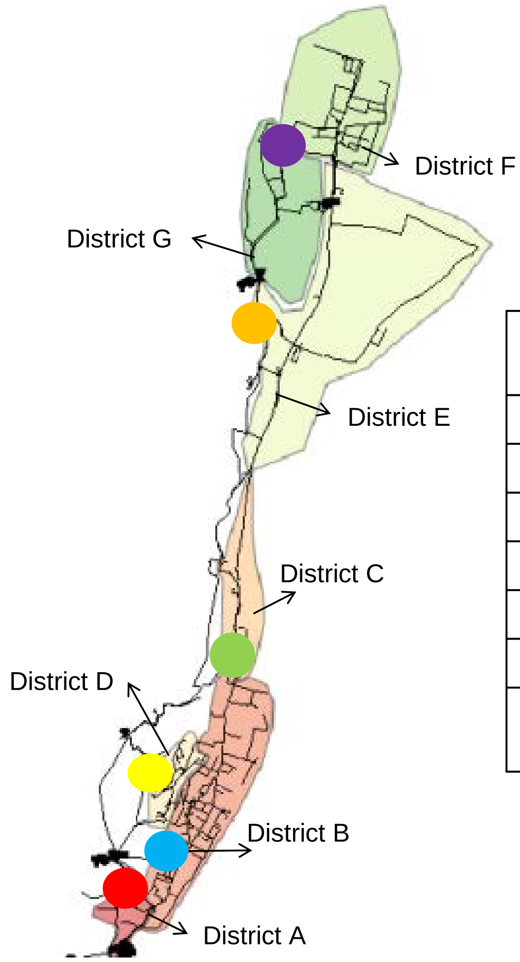


Figure 8.10. Skeletonization of the model

The model includes 11 pumps (names), for which IAG has provided both **characteristic and efficiency curves that have been implemented in the model.** One control (TCV valve) is active, empirically set in order to reproduce the peculiar behaviour of Monterosso tank, according to the available measured data. Monterosso tank is always full. This is because the tank is filled by two different pumping stations, the main of which is operated according to the level in Peroni tank. Peroni (elevation 309.42 m) is fed by Monterosso (elevation 380.80 m), but the intake of the conduit linking each other tanks is placed at the top of Monterosso. That is, such he conduit operates as an overflow, conveying therefore flow rates which are strictly dependent on the pump input.

Table 8.1. Characteristics of the three main tanks of WDS of Langhirano

TANK	ELEVATION (m slm)	VOLUME (m^3)	ONLINE MONITORING
Olive	343.76	545	level
Monterosso	380.80	380	level, flow in
Peroni	309.42	160	level, flow in from Monterosso tank, flow in from Zileri well, flow out



DMAs	PRV current setting (m)
District A	35
District B	60
District C	55
District D	30
District E	15
District F	35
District G	directly supplied by Peroni tank

Figure 8.11. Pressure Management Areas of WDN of Langhirano

8.3.3 Calibration of the model

The model calibration relies on an accurate demand assignment (semi-automatic geo referencing of yearly averaged user consumption) and a tentative distribution of leakages (aimed at reproducing the 35% value declared by IAG). Emitter exponent has been assumed equal to 1.1, considering that the pipes are mainly in HDPE and asbestos cement (only 34% is in steel or cast iron).

Calibration has been carried out with a timestep of 5min, on the basis of the available measured data. The influence of leakages, also in relation to their high magnitude, was considered to be significant and therefore the position and the value of the emitter coefficient were modified using a trail-and-error procedure. Demand patterns were assigned with reference to the flow measurements at the points of direct supply of WDS (pump Jocker flow; tank Peroni outflow towards Stalingrado+Pilastro districts), so without the interference due to the filling of the tanks. Four days were considered, representative of two different working days and two non-working days.

8.4 Alternative operating scenarios

8.4.1 Pressure management (alternative PRV settings)

Referring to the calibration day 78 (working day) the pressure setting at the valves have been modified, still ensuring theminimum pressure required (5m above the roof of each building).

Table 8.2. Current and alternative optimized setting for the PRVs

VALVE (DISTRICT)	CURRENT PRV SETTING (m)	ALTERNATIVE PRV SETTING (m)
A	35	20
B	60	35
C	55	25
D	30	16
E	15	16
F	35	22

8.4.2 Alternative PRV + Pumps settings

Optimization criteria

In order to achieve further energy savings, the ON-OFF settings of the pumps have been slightly modified

The system appeared somehow constrained, therefore relevant changes where not possible. The target has been to make the plants work mainly during the off-peak hours, when the energy cost is supposed to be lower (namely from 0.00 to 8.00 and from 19.00 to 24.00), however still fulfilling the level of service required. These simulations were done assuming the alternative PRV settings.

8.4.3 Alternative scenarios results summary

The system has been simulated according to the previously introduced assumption. The following table reports the leakage rate and daily Energy consumed for the present state and both alternative optimized scenarios.

Table 8.3. Leakage rate and daily energy consumed by the water system

SCENARIO	LEAKAGE RATE (%)	$E_{CONSUMED}$ (KWH/D)
Present state (day 78)	31.08	2356.2
Alternative PRV Settings	24.83	2189.1
Alternative PRV + Pumps Settings	25.42	2082.6

8.5 Microgeneration simulation results

The modelling tool has been applied to all four present state scenarios (four different calibration days) and to the optimized alternative scenarios.

Results are presented through the 3D charts. Each figure caption reports the maximum energy retrievable (peak of the 3D surface) and the related (Qp; Hp) pair.

8.5.1 Present State

The present state has been assessed for days 78 and 82 (working days) and days 66 and 80 (holiday). Here only the results of day 78 (working day) is presented.

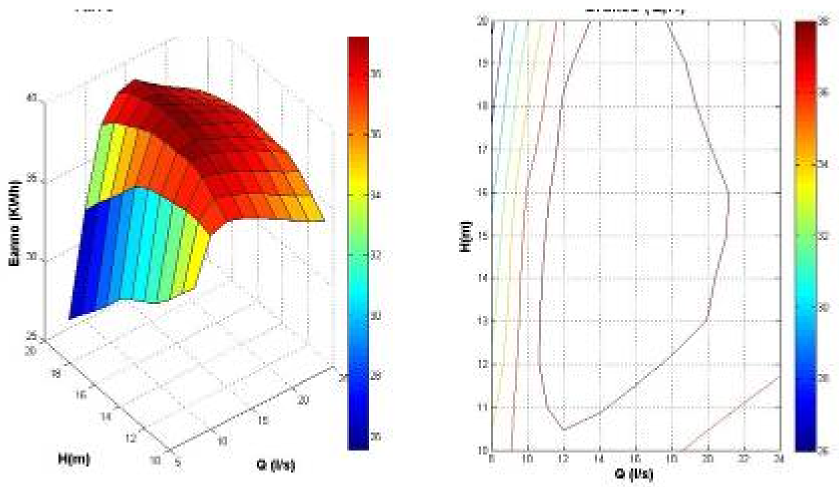


Figure 8.12. Valve B - Present state: Hp = 15 m, Qp = 16 l/s, E_day = 38 kWh

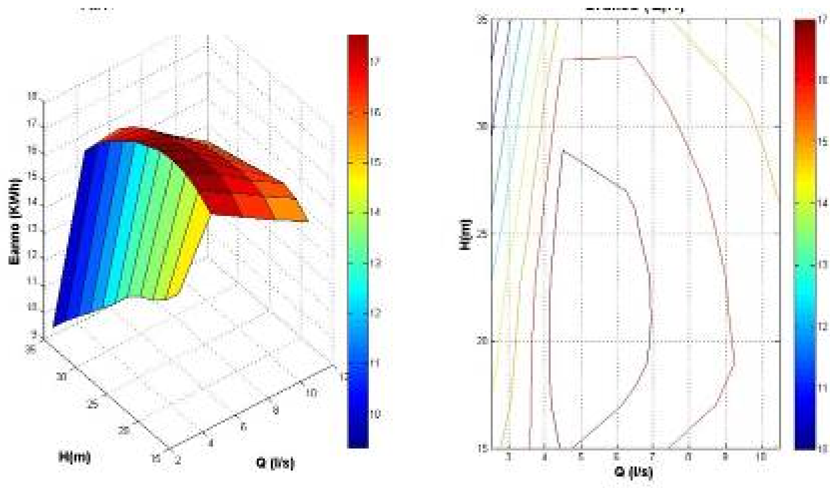


Figure 8.13. Valve E - Present state: Hp = 22 m, Qp = 5.5 l/s, E_day = 17 kWh

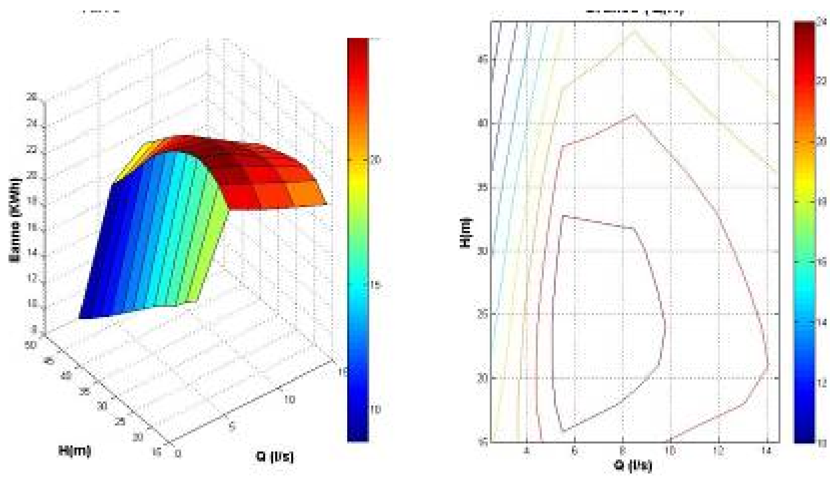


Figure 8.14. Valve C - Present state: Hp = 25 m, Qp = 7 l/s, E_day = 24 kWh

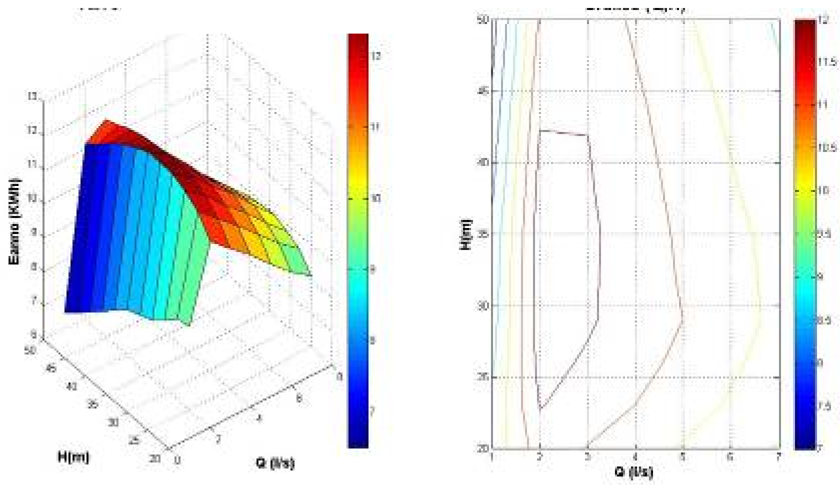


Figure 8.15. Valve D - Present state: Hp = 33 m, Qp = 2.5 l/s, E_day = 12 kWh

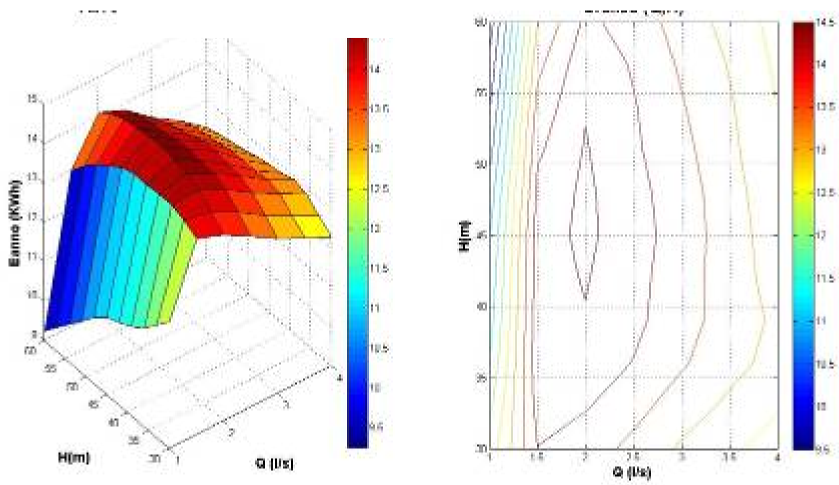


Figure 8.16. Valve A - Present state: Hp = 42 m, Qp = 2 l/s, E_day = 14.5 kWh

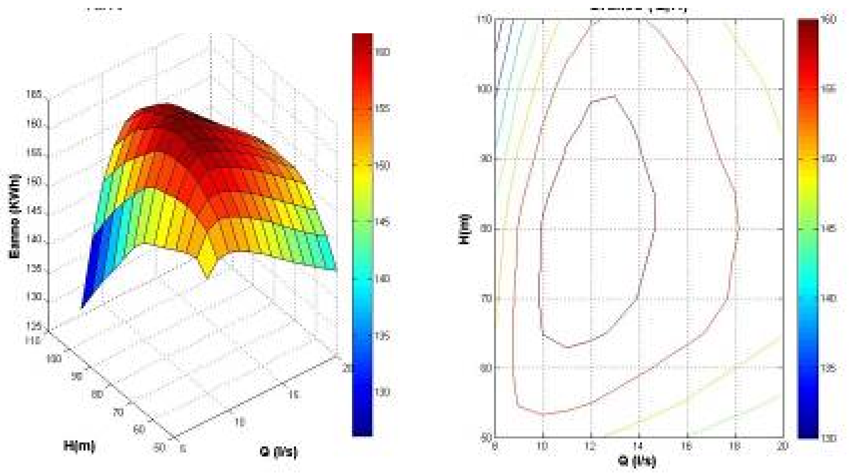


Figure 8.17. Valve F - Present state: Hp = 80 m, Qp = 12 l/s, E_day = 160 kWh

8.5.2 PRV optimized setting

The analysis has been extended to the alternative operating scenarios .

The following charts and results refer to the pressure settings applied to day 78.

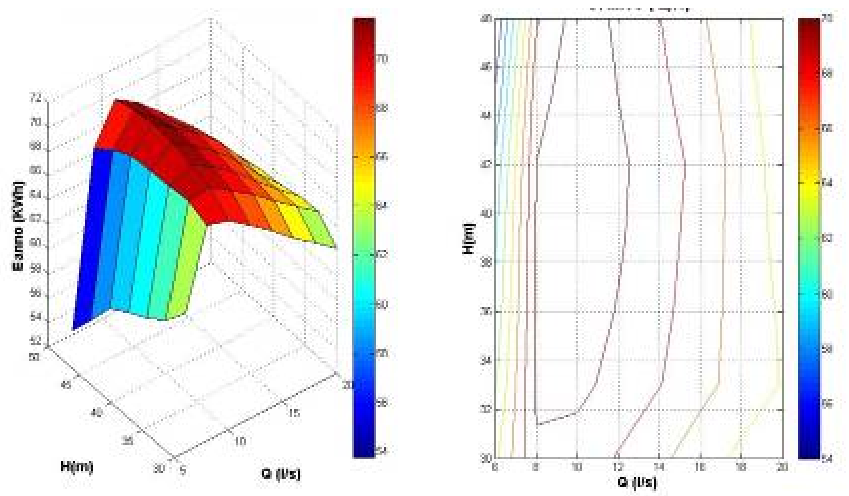


Figure 8.18. Valve B - Present state: Hp = 40 m, Qp = 10 l/s, E_day = 70 kWh

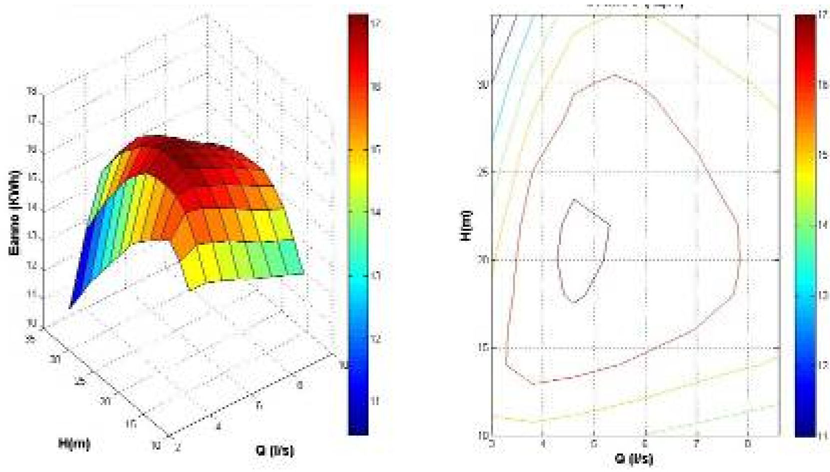


Figure 8.19. Valve E - Present state: Hp = 22 m, Qp = 4.5 l/s, E_day = 17 kWh

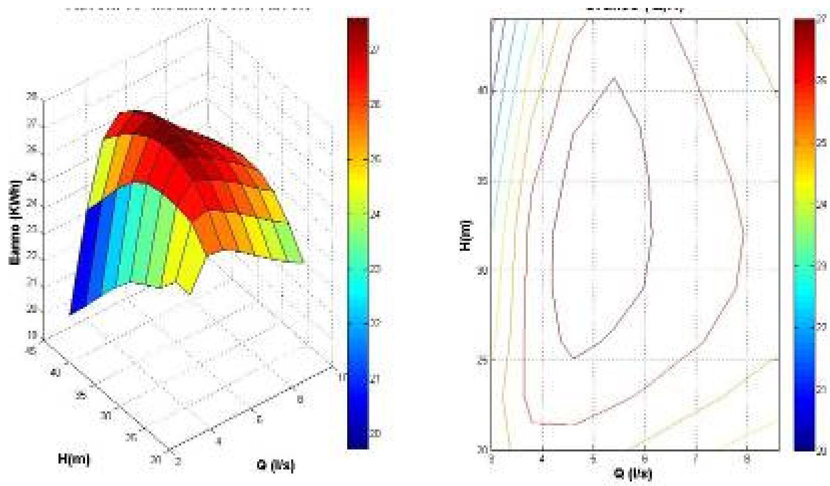


Figure 8.20. Valve C - Present state: Hp = 32 m, Qp = 5 l/s, E_day = 27 kWh

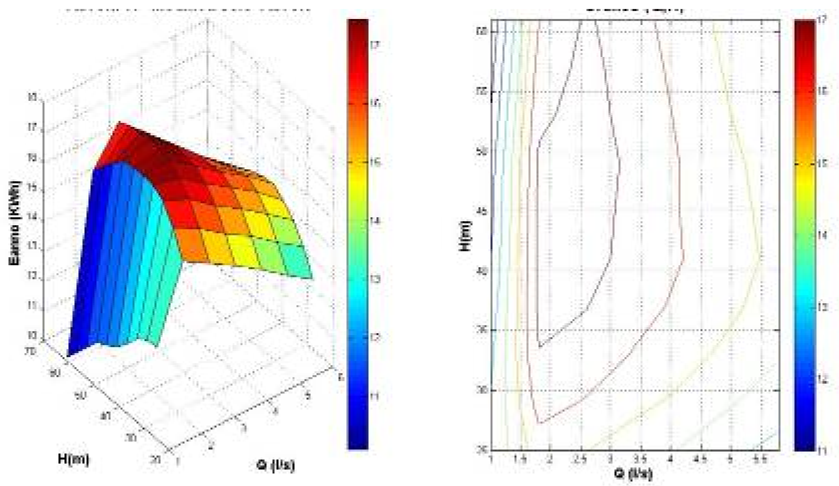


Figure 8.21. Valve D - Present state: Hp = 47 m, Qp = 2.5 l/s, E_day = 17 kWh

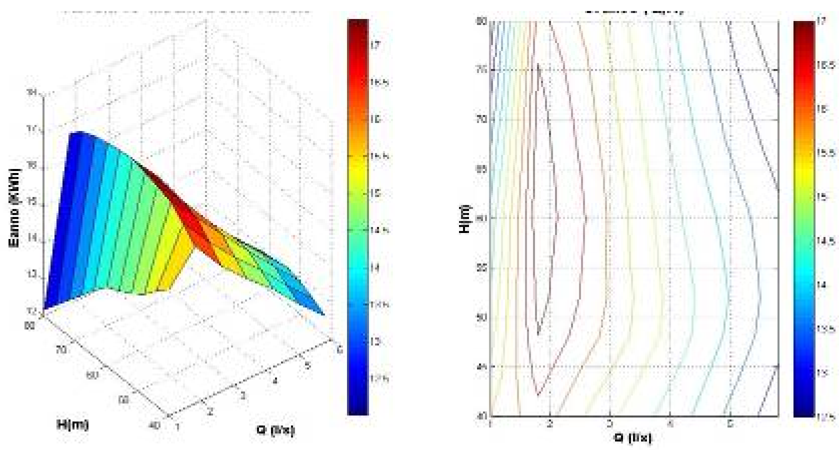


Figure 8.22. Valve A - Present state: Hp = 62 m, Qp = 2 l/s, E_day = 17 kWh

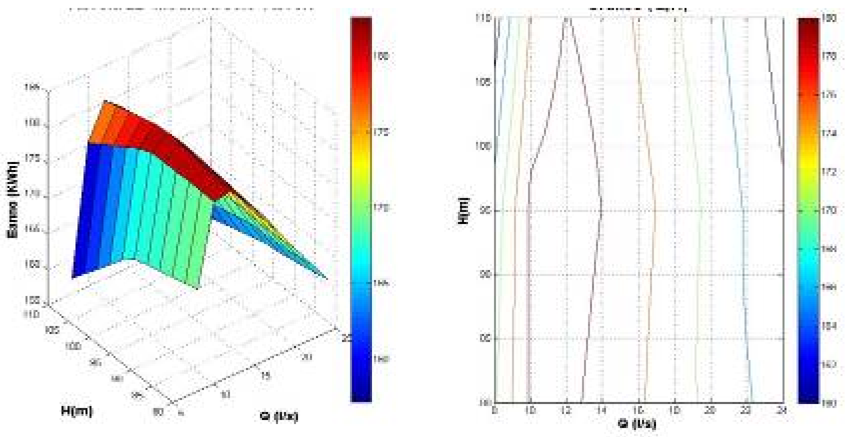


Figure 8.23. Valve F - Present state: Hp = 95 m, Qp = 12 l/s, E_day = 180 kWh

Results of microgenerated energy in the PRV alternative condition are summarized in the following table and compared to the energy retrievable in the present state.

Table 8.4. Energy produced by microturbines at each PRV

VALVE (DISTRICT)	DAY 78 – PRESENT STATE $E_{generated}$ [kWh]	DAY 78 – OPTIM PRV $E_{generated}$ [kWh]	%INCREASE
B	38	70	+84.2
E	17	17	0.0
C	24	27	+12.5
D	12	17	+41.7
A	14.5	17	+17.2
F	160	180	+12.5
Total	265.5	328	+23.5

8.5.3 PRV and Pumps optimized setting

The analysis has been extended to the alternative operating scenarios .

The following charts and results refer to the simultaneous application of the pressure settings and of the modified ON-OFF pump setting, both applied to day 78.

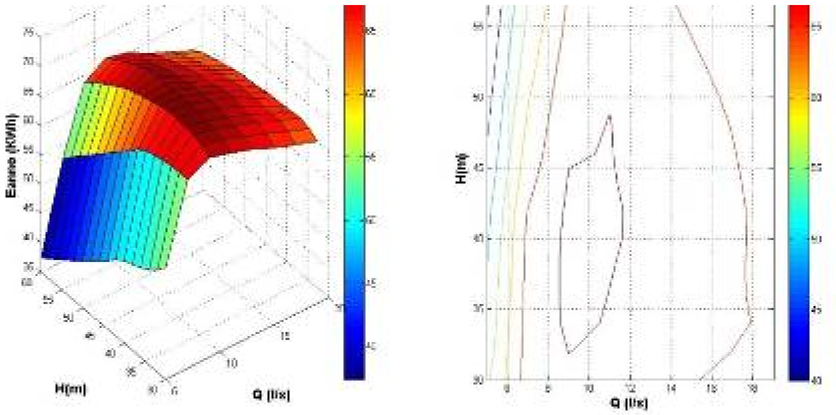


Figure 8.24. Valve B - Present state: Hp = 40 m, Qp = 10 l/s, E_day = 70 kWh

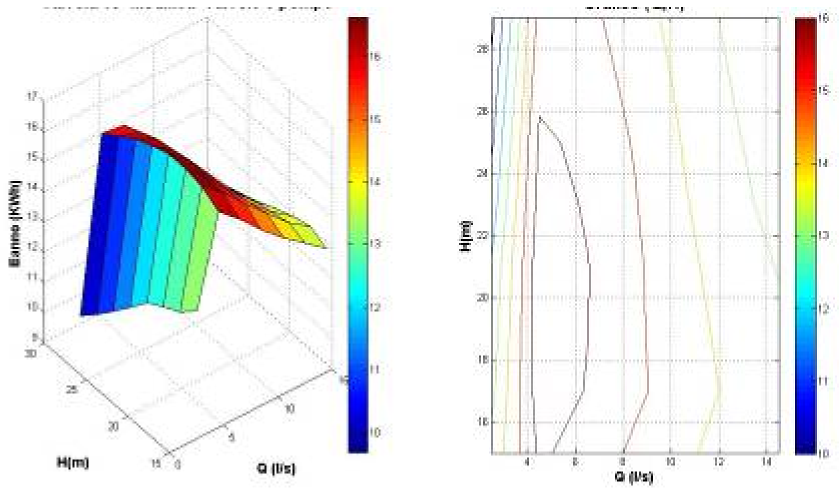


Figure 8.25. Valve E - Present state: Hp = 20 m, Qp = 5 l/s, E_day = 16 kWh

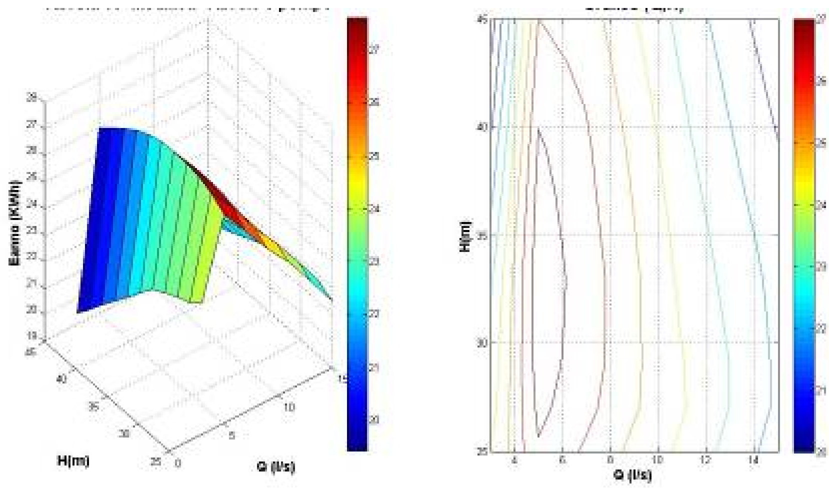


Figure 8.26. Valve C - Present state: Hp = 32 m, Qp = 5 l/s, E_day = 27 kWh

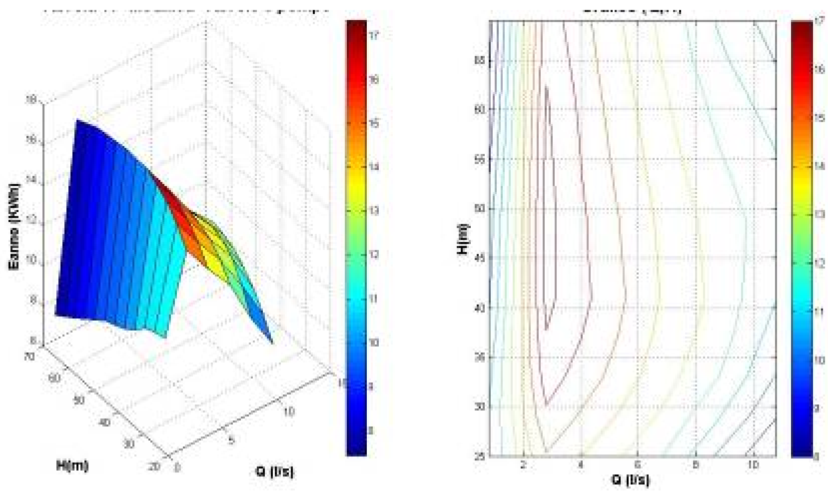


Figure 8.27. Valve D - Present state: Hp = 50 m, Qp = 3 l/s, E_day = 17 kWh

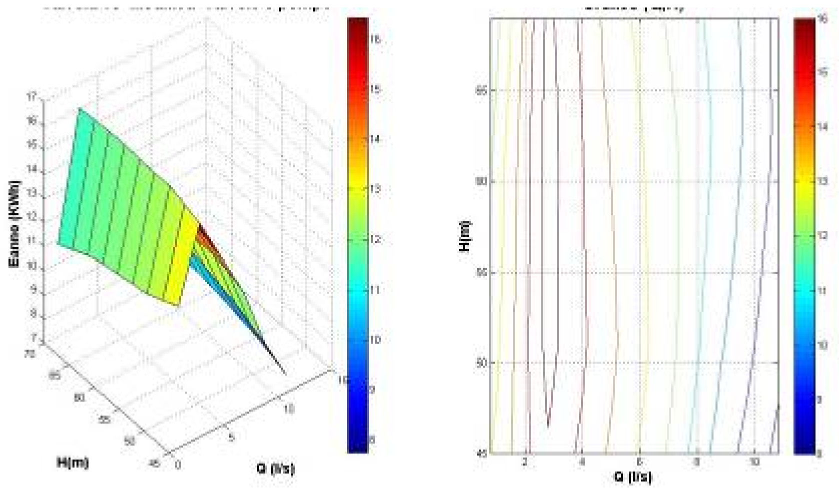


Figure 8.28. Valve A - Present state: Hp = 57 m, Qp = 3 l/s, E_day = 16 kWh

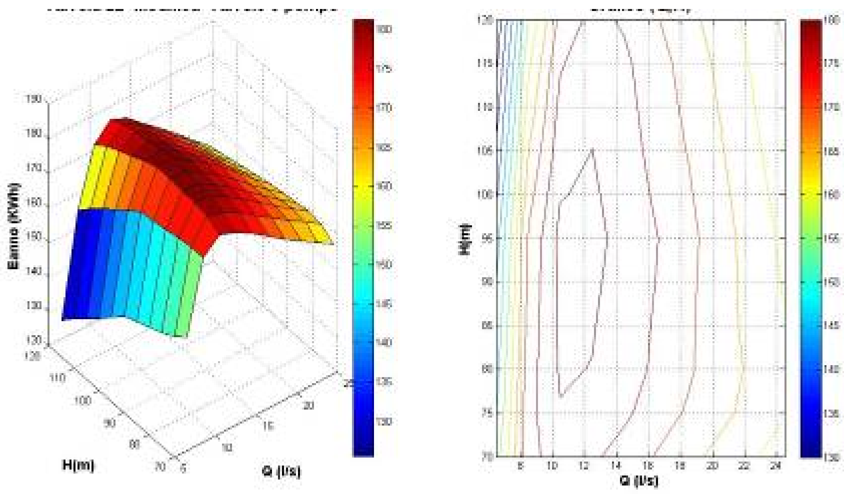


Figure 8.29. Valve F - Present state: Hp = 92 m, Qp = 12 l/s, E_day = 180 kWh

Results of microgenerated energy in the alternative PRV condition and pumps setting are summarized in the following table and compared to the energy retrievable in the present state.

Table 8.5. Energy produced by microturbines at each PRV

VALVE (DISTRICT)	DAY 78 – PRESENT STATE $E_{generated}$ [kWh]	DAY 78 – OPTIM PRV+PUMP $E_{generated}$ [kWh]	%INCREASE
B	38	70	+84.2
E	17	16	-5.9
C	24	27	+12.5
D	12	17	+41.7
A	14.5	16	+10.3
F	160	180	+12.5
Total	**265.5**	**326**	**+22.8**

8.5.4 Results summary and discussion

For the sake of clarity, the following table is presented, introducing all the analized scenarios, both in terms of present state conditions and of alternative settings proposed. The daily microgenerated energy is compared to the daily energy consumed by the system pumps. Water leakage rate is reported as well.

Table 8.6. Summary of Energy consumed, produced and leakage rate for each analyzed scenario.

SCENARIO	E_{cons} [kWh/d]	E_{gener} [kWh/d]	%GEN/CONS	% LEAKAGE
Day 66	2582	256	9.9	27.7
Day 78	2356	265	11.2	31.1
Day 80	2388	267	11.2	29.6
Day 82	2253	260	11.5	31.0
Optim PRV	2189	328	15.0	24.8
Optim PRV+Pump	2083	326	15.7	25.4

8.6 Conclusions

The analysis exhibits several results, which lead to different interesting considerations:

- Despite the amount of energy produced does not allow for the complete self-sustaining of the existing plants, it might however supply energy to auxiliary devices or service buildings used by the water utility

- Larger networks and / or in general able to offer higher hydraulic heads and flows, could lead to increased amounts of energy produced, compared to that consumed. This is mostly true for systems fed also by gravity and not just through pumps (such as Langhirano)

- The inclusion of micro- turbines and their theoretical producibility is not in contrast with the measures taken to save water and energy (further pressure reduction and optimization of pumps operation), as shown in summary in Table 8.6.

All in all, although the absolute value of energy produced by the turbines appear small when compared to the amount spent for the operation of the pumps , the insertion of the machines for the production of energy is in general feasible and not in contrast to other interventions aimed to the improvement of water and energy management of the system.

8.7 References

Awad, H., Kapelan, Z. and Savic, D.A. (2010) Optimal setting of time-modulated pressure reducing valves in water distribution networks using genetic algorithms. Proceedings of the 10th International on Computing and Control for the Water Industry, CCWI 2009, pp. 31-37.

9. HYDRO-GENERATION IN THE WATER SUPPLY SYSTEM OF ATHENS

9.1 Introduction

This chapter presents the potential of micro-generation in the external aqueduct of the Athens water supply system.

9.1.1 Background information

The Athens Water Supply and Sewerage Company (EYDAP SA), the largest of its kind in Greece, serves approximately 4,300,000 customers. EYDAP's estimated annual energy costs are approximately 23 million euro. The majority of energy is used in Psyttalia waste water treatment facilities, as well as for pumping, mainly for water distribution (Nasikas, 2013).

In an attempt to participate in the national effort for sustainable development and rational energy usage, while also diversifying the company's business interests, EYDAP has commenced an ambitious program of energy production from available renewable sources, as well as energy savings in all its business operations. The energy initiatives currently undertaken by EYDAP can be grouped into the following main three categories (EYDAP, 2013):

1. Energy savings: EYDAP is aiming at reducing energy consumption at all office buildings and operating facilities. The company's Energy Department has currently finalised the complete inventory of energy consumption levels at all facilities (over 500 power connections) and has formed a database with energy consumption data. This action will permit EYDAP to more accurately evaluate energy usage at all levels of operation, to amass data necessary for negotiating varied energy rates and to forecast future demand. Within this initiative EYDAP is planning the gradual conversion of its numerous office buildings into more energy efficient "green buildings" by using heat and power cogeneration and solar energy technologies.

2. WWTP energy recovery: EYDAP has constructed in Psyttalia WWTP, the primary wastewater treatment facility for the greater Athens area, two heat and power cogeneration plants; one uses the biogas produced during the sludge digestion process, whereas the second one operates with natural gas. According to EYDAP's strategy regarding the operation of the two heat and power cogeneration plants, the energy produced covers as a priority the needs of the WWTP and any excess electricity is sold to the Electricity Market Operator S.A.

3. Renewable energy generation: EYDAP is currently in the process of converting the energy dissipation works along the external aqueduct network of the Athens water supply system, which ensure normal downstream flow operation and prevent scour and damage to the structure, into energy production plants taking into advantage the

aqueduct's hydropower potential. This investment offers multiple benefits, including environmental benefits through the production of green energy instead of using conventional polluting fossil fuels, as well as financial benefits due to the sale of the produced electricity. Some of these small hydropower plants are already in operation, while the feasibility of others is still being evaluated. At the same time EYDAP is also investigating the possibility of exploiting solar and wind energy near its facilities. Regarding solar energy in particular, the company's plans include the construction of a solar energy park (1.971 MW) within the water treatment facilities in Acharnes, as well as the installation of smaller scale solar panels and solar water heaters to cover operational and auxiliary energy needs.

9.1.2 Small hydropower plants

EYDAP has started converting various energy dissipation works along the external aqueduct network of the Athens water supply system into energy production plants taking into advantage the aqueduct's hydropower potential. The locations of the current and potential hydro plants are shown in Figure 9.1.

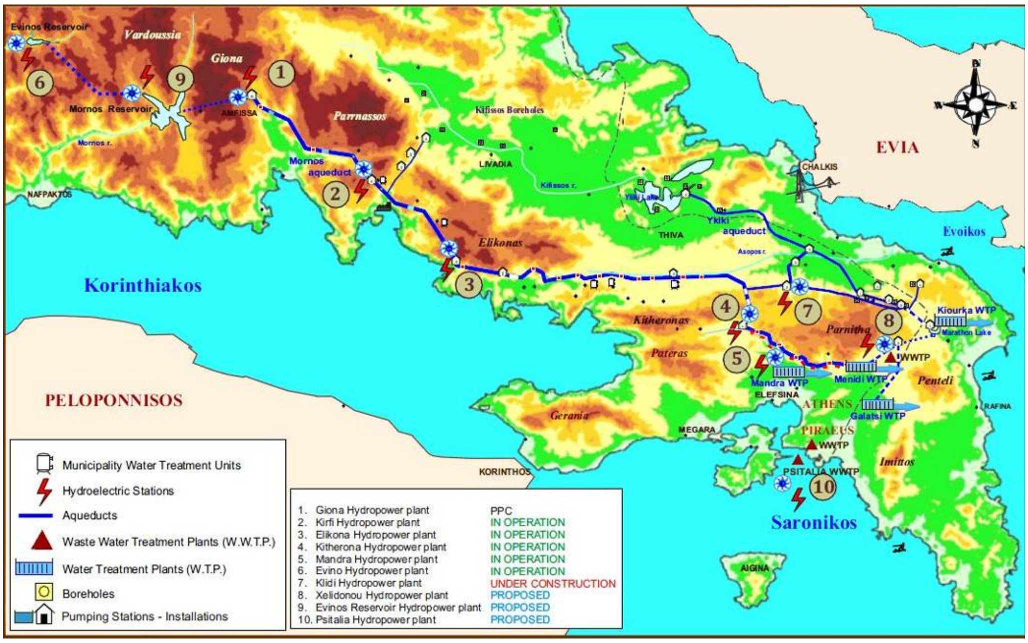


Figure 9.1: Map of the Athens external aqueduct with the existing and proposed hydropower plants (Source: EYDAP)

Table 9.1 contains information on the general characteristics of all hydropower plants in the Athens water supply network that are in operation, under construction, in the design phase or under evaluation, operated by EYDAP or third parties.

Currently six hydropower plants are already in operation in the external aqueduct of the Athens water supply system, five of which are operated by EYDAP with total installed power of 4.06 MW and one by the Public Power Corporation (PPC). Three additional hydropower plants have been approved after the evaluation phase and are going to be implemented in the future; their total installed power is 2.08 MW. The hydro power plants at Klidi, Helidonou and the outlet of Psyttalia WWTP are not yet in operation.

Table 9.1. Existing and proposed hydropower plants in the Athens Water System

HYDRO PLANT NAME	INSTALLED POWER (MW)	ESTIMATED MEAN ANNUAL ENERGY PRODUCTION (GWh / year)	AVERAGE OPERATIONAL FLOW (m^3/sec)	OPERATION STATUS
Giona (PPC)	8.50	40.00	11.5	since 1988
Evinos Env. Flow	0.82	4.00	1.0	since 2009
Kirfi	0.76	5.87	11.0	since 2005
Elikona	0.65	5.03	11.0	since 2005
Kithaironas	1.20	5.73 / 9.50	10.5	since 2007
Mandra	0.63	4.90	10.0	since 2008
Klidi	0.50	3.60	4.2	Under construction (technical issues)
Helidonou	1.23	5.00	5.5	In design phase (licence issued in 2012)
Psyttalia WWTP	0.35	2.50	7.3	In design phase (technical issues)
Giona extension	4.00 (appr.)	-	-	Under evaluation
Evinos - Mornos tunnel	-	-	-	Under evaluation

Source: EYDAP (2013); Brilakis (2009); Brilakis and Chatzidakis (personal communication, EYDAP, July 2012) and Eleftheriadis (personal communication, AKTOR S.A., May 2013)

9.2 Analysis

9.2.1 Description of methodology

The current analysis, which focuses on the external aqueduct of the Athens water supply system, has been carried out with the Urban Water Optioneering Tool (UWOT; Makropoulos et al., 2008; Rozos and Makropoulos, 2012; Rozos and Makropoulos, 2013). UWOT provides a common tool for the combined assessment of water and energy in the whole urban water cycle. The tool has been further developed and modified accordingly in order to be able to deal with the complexity of the Athens water supply system, incorporate necessary components required for the simulation of the different elements of the water-energy nexus in the Athens water supply system and perform relevant energy-related calculations.

Initially the model was simulated for the baseline scenario so that it reflects adequately the current situation it terms of network schematization of the external aqueduct, water balance and water abstractions per source, as well as energy consumption and renewable energy production through the urban water cycle.

Following the satisfactory representation of the current water-energy nexus of the external aqueduct different simulation scenarios were developed corresponding to different phases of implementing various proposed interventions. Each phase includes a different energy-related intervention or combination of interventions (energy saving, pump-storage, solar energy, etc.). The developed scenarios were compared against the baseline scenario and possible impacts on the existing Athens water-energy nexus were estimated using appropriate performance indicators. The results of the analysis were used for an initial assessment of the proposed interventions and the development of an initial water-energy Roadmap for the Athens water supply system.

9.2.2 The Urban Water Optioneering Tool - UWOT

Urban water models often use a hydraulics-based conceptualisation of the urban water network, simulating actual water flows, including runoff, potable water and wastewater. UWOT uses an alternative approach based on the generation, aggregation and transmission of a demand *signal*, starting from the household water appliances and moving towards the source (Rozos and Makropoulos, 2012; Rozos and Makropoulos, 2013; Rozos et al., 2010).

The left panel of Figure 9.2 gives a simplified example of the water flows from the abstraction, through the transmission network to the treatment plant and then to the distribution network. Wastewater and runoff generated in the city are then collected in sewerage networks, treated and disposed to a surface water body. The right panel of Figure 9.2 shows the equivalent representation in UWOT. The upper part (inside the ellipse) includes abstractions, transmission and treatment of raw water (the external water system) whereas the lower part of this panel shows the generation of the demand and the disposal of wastewater and stormwater to water bodies (the internal water system).

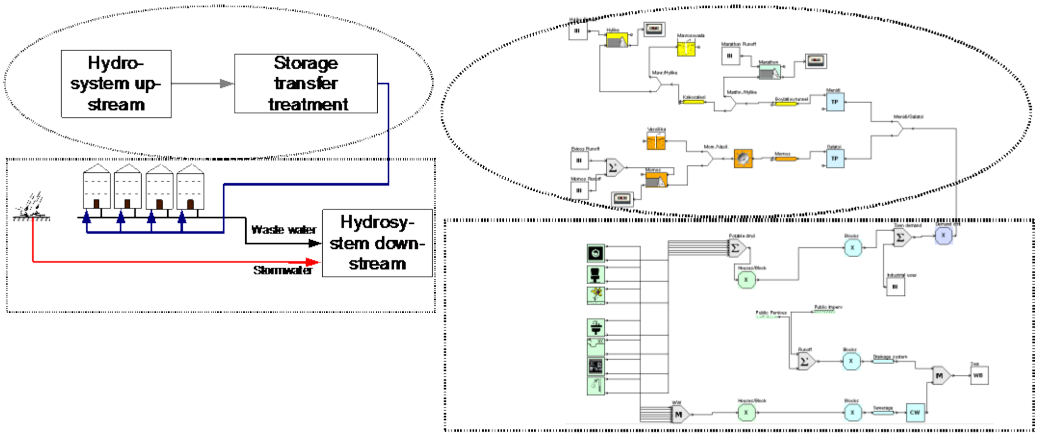


Figure 9.2Left panel: abstract representation of the urban water cycle.

Right panel: source-to-tap modelling of the complete urban water cycle with UWOT. Inside ellipses is the water-supply system, inside rectangles are the water consumption and the drainage system.

Energy consumption or energy production is calculated by various UWOT components, including hydro turbines (HD), aqueducts (AQ) when these represent aqueduct sections with one or more pumping stations, ground water (GW) and treatment plants (TP). For all these components the energy consumption per unit volume (KWh/L) or else specific energy is specified and the energy consumed or produced is estimated by multiplying this value with the incoming demand (up to the capacity).

$$E = \varepsilon \times V \qquad (1)$$

where:

E: Energy consumption or production (KWh)

ε: specific energy consumption or production (KWh/L)

V: volume of water (per model time step) (m^3)

UWOT assumes constant values of specific energy, but in reality specific energy changes with flow and velocity, as well as with changes of upstream and downstream hydraulic head in the case of reservoirs.

9.3 Current situation

9.3.1 The Athens external water supply system

The Athens external water supply system (Figure) extends over an area of around 4,000 km^2 including both surface water and groundwater resources and is operated by EYDAP (Kozanis et al., 2012). The hydrosystem comprises an extensive network of surface water reservoirs, boreholes, aqueducts, pumping stations, hydropower plants and water treatment works and is characterised by a high level of complexity.

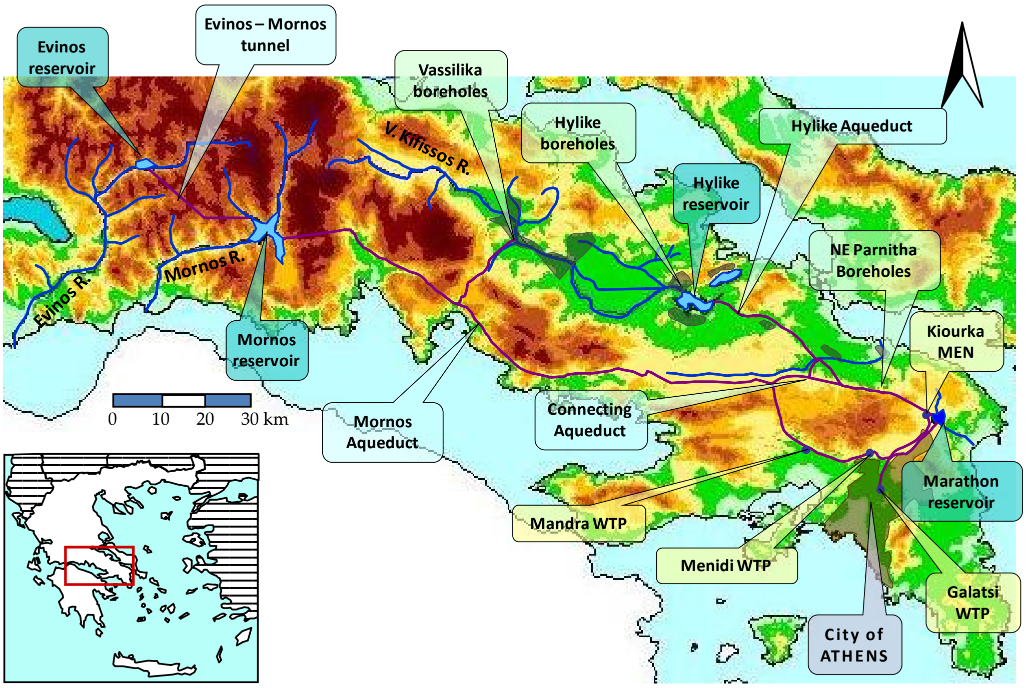


Figure 9.3. The Athens external water supply system

Water resources and storage

The majority of water resources used for supplying water to Athens come from surface sources, which are stored in the four reservoirs of the hydrosystem, Mornos, Evinos, Hylike and Marathon reservoirs (Table 9.2). Out of these reservoirs only Hylike is a natural lake, the rest are artificial.

Mornos and Evinos, which represent the main sources used for the Athens water supply, are used in conjunction with one another, as most of the surface runoff received by Evinos is diverted to Mornos via the Evinos – Mornos tunnel (Figure 9.3) due to its relatively small net storage capacity in comparison to the mean surface runoff received from the upstream catchment area (Table 9.2).

Hylike and Marathon reservoirs both represent auxiliary water sources. Specifically Marathon is mainly used for storing an emergency water supply volume due to its proximity to the city of Athens. On the other hand the reservoir's water levels need to be kept below a certain threshold in order to minimise flood risk of the downstream populated areas. Therefore, tight limits have been set for Marathon's water level fluctuation (Efstratiadis et al., 2009).

Table 9.2. Main characteristics of the Athens water system surface water sources and reservoirs

RESERVOIR NAME	CATCHMENT AREA (km^2)	MEAN ANNUAL SURFACE RUNOFF (hm^3)	TOTAL STORAGE CAPACITY (hm^3)	NET STORAGE CAPACITY (hm^3)	MEAN ANNUAL ABSTRACTIONS (hm^3)
Mornos	588.1	234.1	763.71	630.23	291.0
Evinos	351.9	276.1	137.63	112.05	202.4
Hylike	2466.6	294.1	594.75	584.75	83.3
Marathon	118.0	13.4	42.85	32.20	68.8

Source: Makropoulos et al. (2010)

Groundwater from three aquifers is used today as a back-up water source. EYDAP currently holds approximately 70 boreholes that are classified in six different groups. These have a total power of 17 360 Hp and pumping capacity of approximately 390 000 m^3/d (Efstratiadis et al., 2009).

Aqueducts

The Athens external water supply system includes an extensive and in some case complex network of aqueducts that conveys water from the different water resources to the four water treatment plants supplying the city of Athens. The external aqueduct network includes open channels, tunnels, siphons and closed pipes; the total length of the all water conveying elements is approximately 440 kilometres (Table 9.3).

The primary external aqueduct network includes two main branches; the north and south branch (Figure) (Rozos and Makropoulos, 2013). The north branch conveys water from Hylike Lake, Marathon reservoir and the boreholes groups of Ougra, S.W. Hylike and Mavrosouvala towards Kiourka and Galatsi water treatment plants. This is an energy intensive branch as it requires the use of pumping stations at various locations along the network. However, its use is required in order to minimise losses from Hylike lake that increase as water are high (Katerinopoulou, 2009). The south branch conveys water from Evinos and Mornos reservoirs, as well as from the borehole group Vassilikon-Paroriou towards Mandra, Menidi and Galatsi water treatment plants. The water is transported through gravity and currently five hydropower plants exploit the hydropower potential of the south network branch.

Table 9.3. Main characteristics of external aqueduct network

TYPE OF AQUEDUCT	AQUEDUCTS	TOTAL LENGTH (KM)
Main	Mornos, Evinos, Hylike, Kakosalesi, Marathon - Galatsi	300
Connecting	Marathon connecting, Distomo, Kiourka – Menidi, Kremmada – Kleidi	105
Auxiliary	Vasilikon – Paroriou GW, SW Hylike GW, Ougra GW, Viliza GW, Hylike floating, Diversions (Viliza, Malakasa)	34

Source: Makropoulos et al. (2010)

Besides the primary aqueduct network, the hydrosystem also includes connecting and auxiliary aqueducts. The most significant connecting aqueduct is the Marathon connecting aqueduct that links the south and north branches via Kleidi (Table 9.3). Despite the fact that the particular connecting aqueduct has been designed to allow bi-directional flow between the main branches, at the moment only the gravity flow direction actually functions due to technical problems (Makropoulos et al., 2010). There are also other connecting aqueducts allowing water transfers between the four water treatment plants. Auxiliary aqueducts include among others pipes that transport water abstracted from the boreholes to the main network and diversions.

Pumping stations

The pumping stations along the Athens external aqueduct network enable the water transfer from sources of lower elevations (Hylike lake, boreholes) towards higher elevations (Marathon, Mornos aqueduct). The operation of pumping stations is of particular importance for this study that explores the water energy nexus of the Athens hydrosystem.

The total installed power of the pumping stations of the external water supply network amounts to 97660 Hp; the most significant ones are (Efstratiadis et al., 2009):

- *Hylike central pumping station and Hylike floating pumping station*: These two pumping stations transfer water from Hylike Lake towards Hylike aqueduct. Both pumping stations operate when the lake's water level falls below 71.0 metres. The central pumping station is also used for the conveyance of groundwater abstractions from the borehole groups of SW Hylike and Ougra.

- *Viliza pumping station*: This pumping station in conjunction with a series of other smaller ones conveys water towards Marathon reservoir via Hylike aqueduct.
- *Distomo pumping stations (AD1, AD2 and AD3)*: These pumping stations transfer water abstracted from the borehole group Vasilikon – Paroriou towards Mornos aqueduct.
- *Kremmada and Asopos pumping stations*: The two pumping stations transfer water from Hylike to Mornos aqueduct.

Hydropower plants

Currently five small hydropower plants are in operation on the south branch of the Athens external water supply system, on Mornos aqueduct.

9.3.2 Setting up the baseline scenario

As discussed previously Athens external water supply system is quite complex, therefore setting up the intricate network in UWOT and achieving an appropriate network schematisation is no easy task; some simplifications and assumptions were necessary.

The structure of the Athens urban water system has been set-up in UWOT so that the resulting schematisation resembles as much as possible the actual urban water system. Figure 9.4 presents the network schematisation of the Athens external water supply system in UWOT's *Spatial View*.

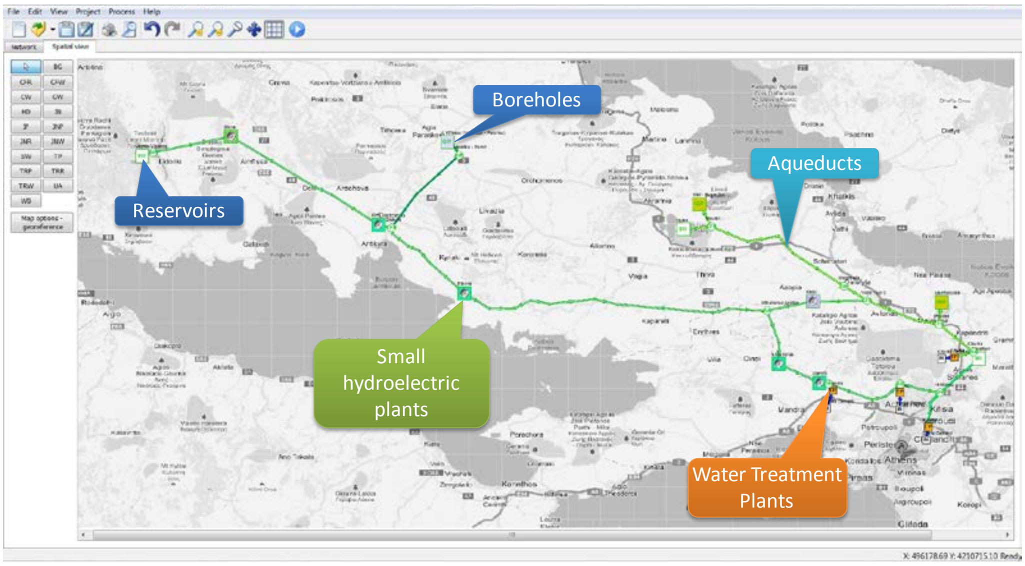


Figure 9.4: UWOT schematisation of the Athens external water supply system – Spatial / GIS view

For the schematisation of the baseline model several simplifications have been adopted in order to reduce model complexity. This resulted in a *Network View* schematisation in UWOT of the Athens external water supply system for the baseline scenario.

The representation of the Athens external water supply network employs various UWOT components. For each component used different brands were specifically developed for the adequate representation of the various actual components of the Athens water supply system. Each UWOT component brand was assigned with appropriate technical specifications, such as water losses, length, capacity, energy use, etc. Regarding financial specifications, i.e. capital and operational costs, general values from literature were used..

Other input data include:

- Water demand: Monthly water demand timeseries for each water treatment plant were created based on current historic demand data at the outlets of each water treatment plant (Makropoulos et al., 2010 and Efstratiadis et al., 2009). The sum of these demands represents the water demand of the entire city of Athens, and the annual value is approximately 415 hm^3.

- Climatic Data - Reservoir Inflows: Monthly synthetic timeseries were used as inflows to the reservoirs of the hydrosystem. These inflows are the sum of surface runoff from the catchment area upstream of each reservoir and the direct rainfall on the reservoir.

9.3.3 Results – Baseline scenario

Water Balance

Having completed the model setup for the baseline scenario the model was run with a monthly time step for 100 years using the synthetic inflow timeseries and average monthly water demands as described in Section 0. The results of the baseline model were compared against the results of Hydronomeas water management model (Koutsoyiannis et al., 2002) developed for the analysis in Makropoulos et al. (2010) for validation purposes.

Table 9.4 presents a comparative analysis of the water balance between UWOT and Hydronomeas by comparing average annual values calculated from the entire simulation period. Abstractions from each reservoir are compared, as well as total groundwater abstractions and aqueduct losses.

The comparison of the water balance average annual values shows an overall good performance of the UWOT baseline model for the Athens external water supply network. The good fit between the two models indicates that UWOT model assumptions used for the baseline scenario are valid and have not compromised model performance.

However, there are some differences in the performance of the two models since they have different conceptualisation and have been setup in a different manner to some extent, using a few different assumptions and hydrosystem operational rules.

More specifically, it can observed from the model comparison that UWOT overall predicts less abstractions from the hydrosystem in comparison to Hydronomeas. This can be attributed to the fact that in Hydronomeas model some relatively low additional water demands have been taken into account, including urban water supply of communities close to the main aqueducts and irrigation of nearby agricultural areas, whereas in UWOT only Athens water demand has been taken into account (and indirectly some irrigation abstractions from Hylike lake).

Table 9.4. Average annual water balance (hm3/y) - Model results comparison UWOT & Hydronomeas

	YLIKI ABSTR. (hm^3/y)	MORNOS & EVINOS ABSTR. (hm^3/y)	MARATHON ABSTR. (hm^3/y)	GROUNDWATER ABSTRACTIONS (hm^3/y)	AQUEDUCT LOSSES (hm^3/y)	TOTAL ABSTR. (hm^3/y)
UWOT	66.419	378.025	15.898	9.400	57.82	469.742
Hydronomeas	70.596	401.424	11.628	8.688	64.02	492.336
% Difference	-5.92 %	-5.83 %	36.72 %	8.19 %	-9.62 %	-4.59 %

In terms of groundwater abstractions UWOT shows more groundwater abstractions from the simulated borehole groups. This difference is probably caused by the fact that Hydronomeas also includes a few smaller borehole groups that have been omitted from UWOT, therefore the total groundwater abstractions predicted by Hydronomeas are actually higher than the value shown in Table 9.4.

Marathon abstractions in UWOT are significantly higher than the ones in Hydronomeas. The reason behind this difference is that the operational rules for Marathon reservoir have been implemented in a different way in two models. The most significant difference is that UWOT assigns a maximum abstraction volume that remains constant throughout the year, whereas Hydronomeas uses more specific and strict operational rules that have a seasonal variation, allowing ultimately the abstraction of less water (see Makropoulos et al., 2010).

The fraction of groundwater abstractions is very small, only 2% of the average annual total water abstractions that are approximately 570 hm^3. As expected July is the month with the highest water abstractions. The majority of surface water abstractions come from Mornos aqueduct, i.e. from Mornos and Evinos reservoirs. On average groundwater abstractions obtain their highest values during the period of September to November, when reservoirs' water levels are at their lowest.

Energy Balance

Following the water balance analysis, the energy balance in terms of energy consumption and renewable energy production was examined for the baseline scenario.

Energy consumption

UWOT energy consumption results were compared against energy consumption results estimated by Hydronomeas model (Makropoulos et al., 2010). Table 9.5 presents the comparison of the energy balance estimated by the two models in terms of average annual energy consumption. It can be observed that in general there is a quite strong agreement between the estimates of the two models. However, the results indicate that UWOT slightly overestimates energy the total consumption. The reason behind this small difference lies in the fact that in UWOT baseline model we have used more accurate specific energy data for an energy intensive pump system located at Kiourka water treatment plant. This data was supplied by EYDAP (Nasikas, 2013) as a result of a specific on-site energy audit at the specific location.

Figure 9.5 shows the average seasonal variation in energy consumption in all the sections of the Athens external water supply system. According to UWOT the estimated average annual energy consumption reaches 90.6 GWh, the biggest part of which is consumed in pumping water through the Hylike aqueduct system.

Table 9.5. Average annual energy balance (hm3/y) - Model results comparison UWOT & Hydronomeas

	HYLIKE AQUEDUCT PUMPING (GWH/Y)	DISTOMO CONNECTING AQUEDUCT PUMPING (GWH/Y)	HYLIKE GROUNDWATER (GWH/Y)	DISTOMO GROUNDWATER (GWH/Y)	TOTAL ENERGY CONSUMPTION (GWH/Y)
UWOT	79.960	4.610	5.250	0.760	90.58
Hydronomeas	76.704	4.524	4.824	0.744	86.80
% Difference	4.24 %	2.00 %	8.73 %	1.89 %	4.36 %

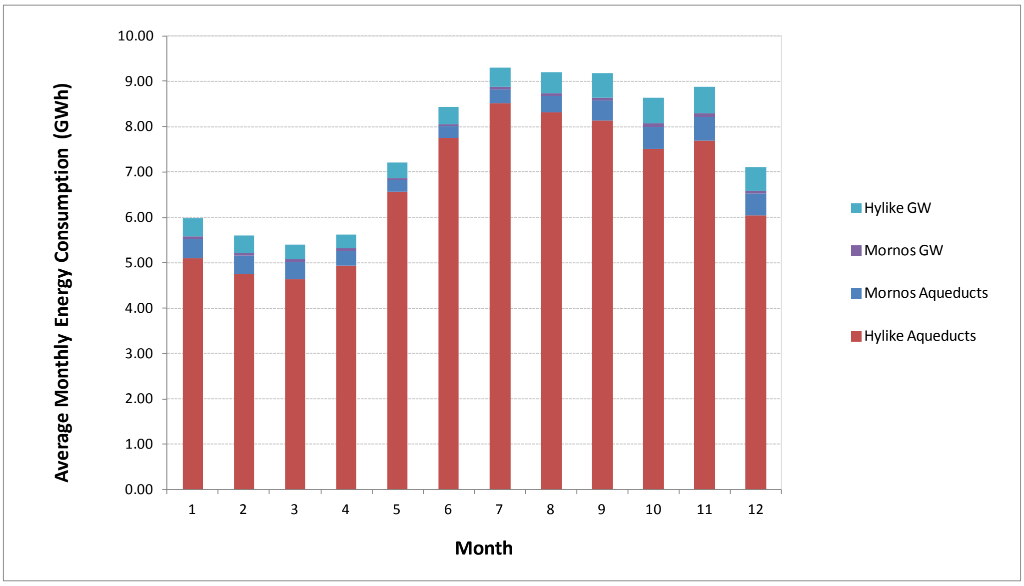


Figure 9.5: Average monthly energy consumption per water source along the external water supply system

Energy production

Hydropower energy production results estimated by UWOT were compared with data of actual renewable energy sold to the Electricity Market Operator (LAGIE). According to the estimates of the UWOT baseline model the average annual renewable energy produced by EYDAP's existing hydropower plants of the external aqueduct is approximately 20.47 GWh, which is very close to the actual average annual renewable energy production of 20.62 GWh. Furthermore, Giona hydropower plant that is operated by the Public Power Corporation (PPC) produces another 40 GWh annually (Figure 9.6).

Figure 9.7 displays the current average seasonal variation in energy consumption and renewable energy production by the existing hydropower plants operated by EYDAP. A significant amount of energy is currently produced by the existing hydropower plants, which corresponds to 22.6 % of the total energy consumed in the Athens external aqueduct.

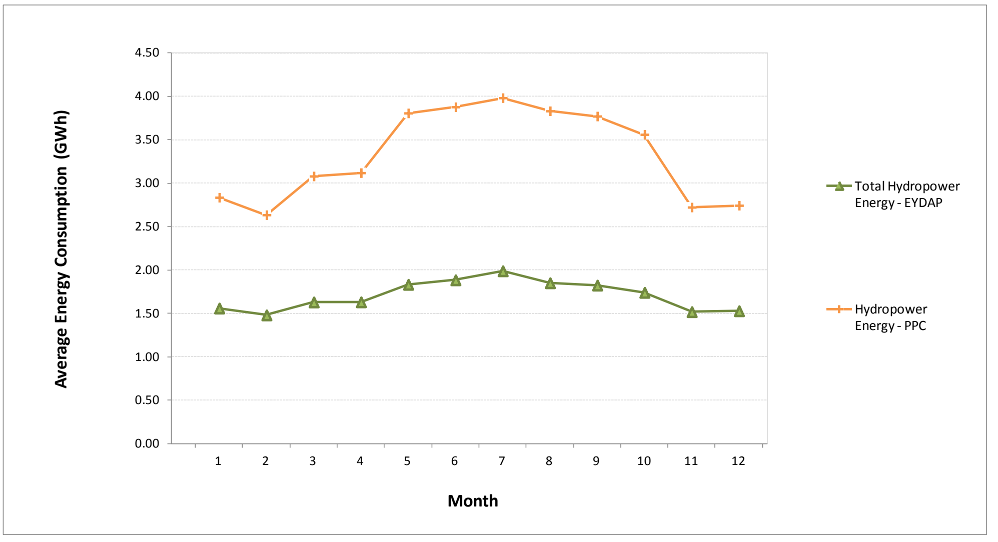


Figure 9.6: Average monthly energy production from hydropower plants of the Athens external water supply system

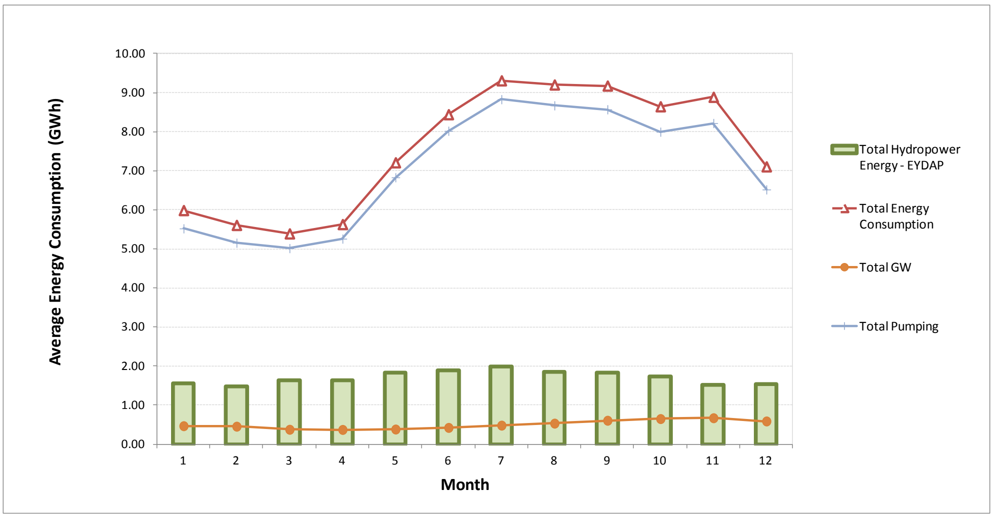


Figure 9.7. Average monthly energy consumption and production along the external water supply system

9.4 Proposed water–energy interventions

9.4.1 Description of suggested water-energy interventions

The NTUA research team has identified and prioritised various energy-related interventions and measures; ones that would result in the reduction of energy consumed in the external aqueduct and others that would further exploit the available renewable energy potential of the urban water cycle and reduce EYDAP's net energy needs and carbon footprint. The analysis and proposed interventions mainly focus up to this moment on the Athens external water supply system as far as the four water treatment plants. However, the aim is to expand the analysis downstream the water treatment plants and incorporate Athens' entire urban water cycle.

The possible interventions were identified from various information sources available from EYDAP (Brilakis, 2009; EYDAP, 2013), as well as from closer collaboration with the water company via a series of meetings and workshops (Nasikas, 2013; Brilakis and Chatzidakis personal communication, EYDAP, July 2012). The examined energy related interventions have different implementation timeframes and have been grouped accordingly into four phases, namely immediate, short-term, medium term and long term (Table 9.6).

Table 9.6. Identified energy-related interventions

PHASE	IDENTIFIED INTERVENTIONS
Phase 1: Immediate	Pump Replacement: Kiourka WTP Operation improvement of existing HPP: Kithaironas HPP New planned HPP in operation: Klidi HPP
Phase 2: Short - term	New planned HPP in operation: Helidonou HPP New planned HPP in operation: Psittalia WWTP HPP Planned PV Farm in operation: Acharnes /Menidi WTP
Phase 3: Medium - term	New proposed HPP: Giona HPP - exploitation of additional flow
Phase 4: Long – term Options A & B	New proposed HPP: Outlet of Evinos – Mornos tunnel (*Option A*) Pump storage scheme: Between Evinos and Mornos reservoirs (*Option B*)

The short-term interventions within the first two phases include interventions, such as pump replacements, hydropower plant improvements and developments, which are in EYDAP's strategic plans. The longer term interventions contained in the following two phases deal with proposed renewable energy projects that are not currently in the company's agenda. Phase 4 includes two different intervention options; the first follows a more conservative approach, whereas the second one suggests a more innovative renewable energy project.

The analysis of the specified interventions is included in the following paragraphs.

9.4.2 Phase 1 scenario – Analysis & Results

Set-up / Schematisation

The energy related interventions included in Phase 1 are very short term interventions and include the replacement of the energy intensive pumps at Kiourka water treatment plant, the operation improvement of Kithaironas existing hydropower plant, as well as the completion and operation of Klidi hydropower plant which is located on Marathon connecting aqueduct. The structure of the Athens hydrosystem network in UWOT practically remains the same as in the baseline scenario apart from the addition of the new hydropower plant Klidi (Figure 9.8).

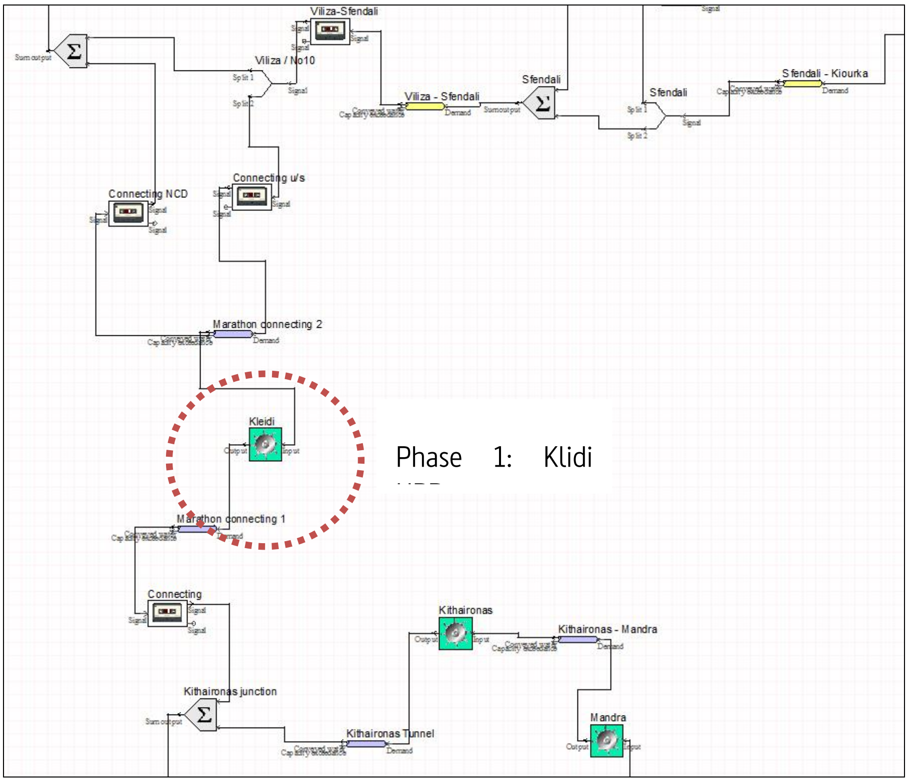


Figure 9.8. Detail of UWOT schematisation of the Athens hydrosystem – Klidi HPP (Phase 1)

For the two existing elements with improved operation, new UWOT brands were created that have lower specific energy values. For the aqueduct at Kiourka water treatment plant these values were calculated according to data from the specific on-site energy audit (Nasikas, 2013), whereas for Kithaironas improved hydropower plant using the anticipated mean annual energy production included in Table 9.1. A new hydro turbine component was also created for the new hydropower plant at Klidi, whose technical specifications were calculated according to the specific hydropower plant's general characteristics in Table 9.1.

Model results

Figure 9.9 displays a set of summary results from Phase 1 model and specifically the average monthly energy consumption, as well as EYDAP's average monthly renewable energy production along the external water supply network. In comparison toFigure 9.7 of the baseline scenario the graph has a very similar pattern with the total pumping energy and total energy consumption slightly lower and the total hydropower energy increased.

According to model estimations, after the implementation of Phase 1 interventions the average annual total energy consumption up to the water treatment plants falls to 87.46 GWh, the average annual energy production from EYDAP's hydropower plants is 23.65 GWh and the renewable energy fraction climbs up to 27.04 %

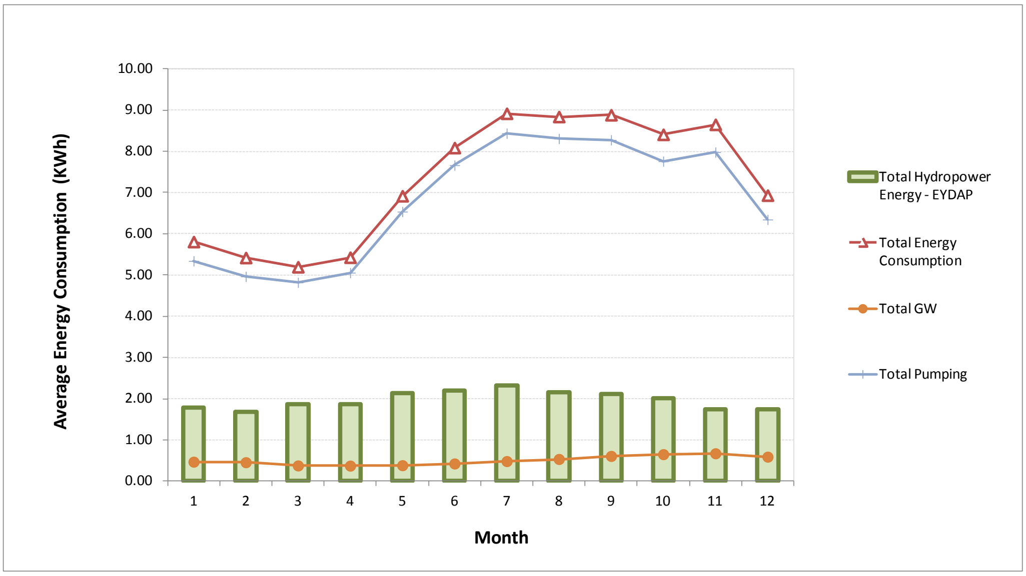


Figure 9.9. Average monthly energy consumption and production along the external water supply system - Phase 1

9.4.3 Phase 2 scenario – Analysis & Results

Set-up / Schematisation

The short term interventions included in Phase 2 include the addition of two new hydropower plants at Helidonou and at the outlet of Psyttalia waste water treatment plant, as well as the operation of the planned photovoltaic farm in Acharnes at Menidi water treatment plant.

The model developed for Phase 2 however, includes only the new hydropower plant at Helidonou, since Psyttalia hydropower plant cannot be added at the moment since the specific plant is not located at the external water supply network and the current Athens model extents only up to the water treatment plants and doesn't include the rest of the urban water system. Furthermore the PV farm cannot be added to the model because UWOT only includes elements directly connected to the urban water cycle.

The only change therefore in the structure of the Athens hydrosystem network in UWOT in comparison to Phase 1 model is the addition of the new hydropower plant at Helidonou (Figure 9.10)

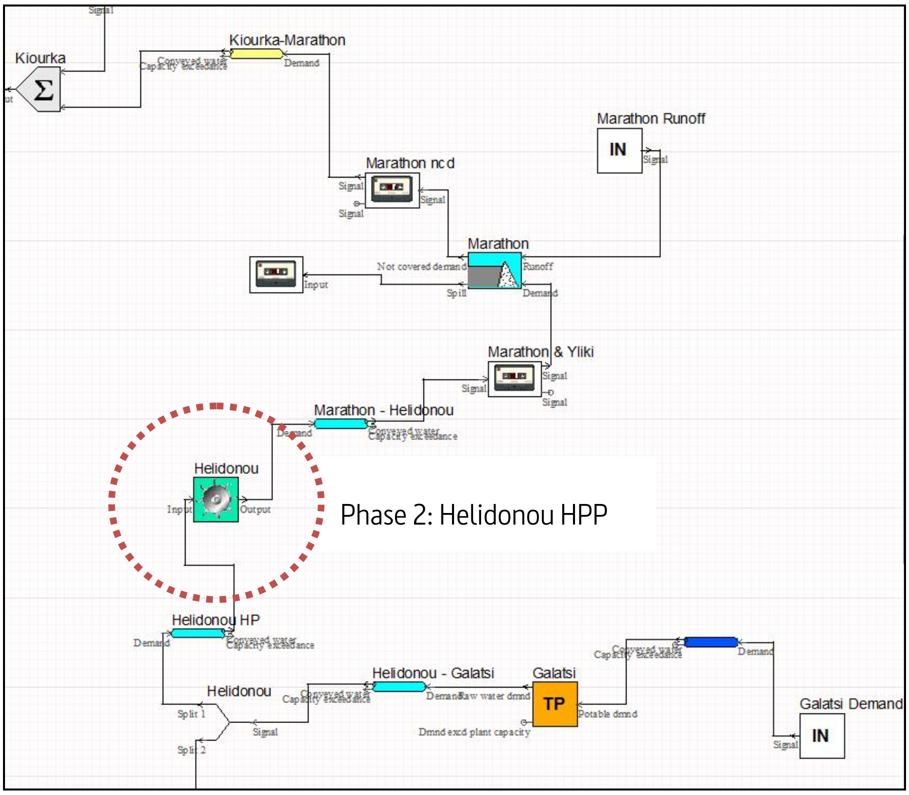


Figure 9.10. Detail of UWOT schematisation of Athens hydrosystem – Helidonou HPP (Phase 2)

Model results

Figure 9.11 displays the average monthly energy consumption, as well as EYDAP's average monthly renewable energy production along the external water supply network, after the simulation of Phase 2 model. As mentioned before these results only include the new hydropower plant at Helidonou and do not include the rest of the interventions.

In comparison to the results of Phase 1 model there is no change in total energy consumption, as expected, since no energy saving measures were implemented at this stage. Again the monthly pattern of renewable energy production is very similar to the baseline and Phase 1 scenario, but it has increased from the addition of the Helidonou HPP.

According to model estimations, after the implementation of Phase 2 interventions the average annual total energy consumption up to the water treatment plants remains the same at 87.46 GWh, the average annual energy production from EYDAP's hydropower plants increases to 25.71 GWh and the renewable energy fraction rises to 29.39 %

The impact of the two additional interventions that were not included in the model was taken into account only as an average annual value of estimated renewable energy production. The estimated annual energy production for Psyttalia WWTP hydropower plant was taken from Table 9.1 and for the photovoltaic park it was estimated according to an average number of 1400 operating hours per year to approximately 2.8 GWh. Following the application of all Phase 2 interventions the average annual energy production from all EYDAP renewable energy sources is 31.01 GWh and the renewable energy fraction rises to 35.45 %.

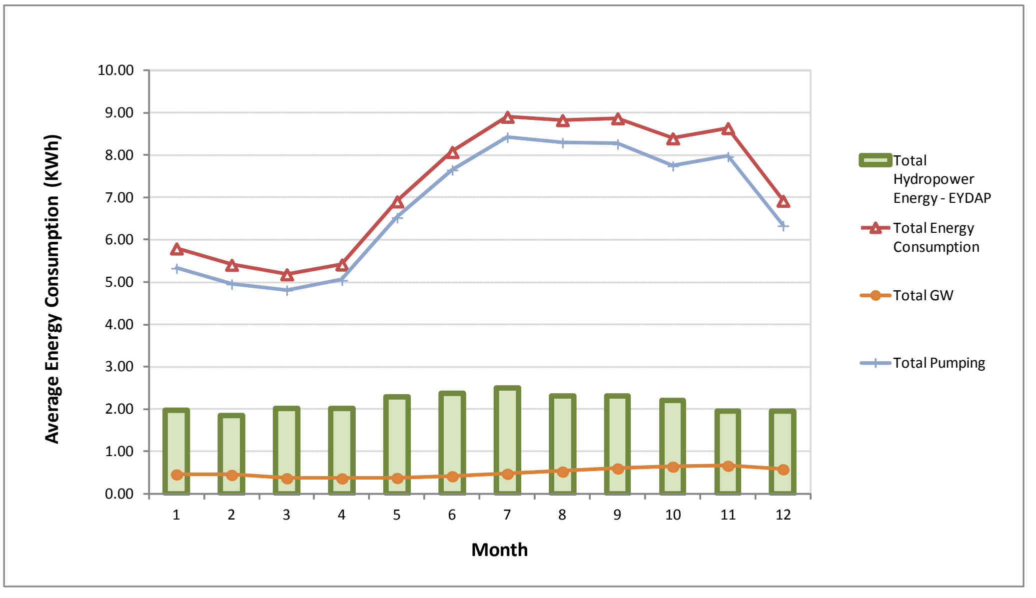


Figure 9.11: Average monthly energy consumption and production along the external water supply system - Phase 2

9.4.4 Phase 3 scenario – Analysis & Results

Set-up / Schematisation

Phase 3 includes the development and operation of only one new hydropower plant, which is located at Giona at the outflow of Giona tunnel. This suggested measure is included in the medium term interventions mostly because it is not currently in EYDAP's agenda, however the implementation shouldn't require too much time and resources since a lot of infrastructure is already in place because of the existing hydropower plant.

The proposed hydropower plant would exploit the flows that are not currently used by the existing hydropower plant operated by the Public Power Corporation (PPC). According to EYDAP (Brilakis personal communication, 2012) 4 MW of additional power could be exploited. For the purposes of this research study the proposed hydropower plant has been named “Giona extension”.

Giona, the existing hydropower plant, has been designed to operate with incoming flows between 7.5 and 14.5 m^3/sec, and has an average operational flow of 11.5 m^3/sec (Table 9.1). Effectively, when flows are lower than 7.5 m^3/sec or higher than 14.5 m^3/sec the additional hydropower potential remains unexploited and the flow goes through EYDAP’s energy dissipation works.

The proposed hydropower plant, Giona extention, is therefore suggested to utilise a) low flows lower than 7.5 m^3/sec and b) the excess from high flows higher than 14.5 m^3/sec and up to 18 m^3/sec, which is the current carrying capacity of Mornos external aqueduct system due to downstream limitations. It should be noted however that Giona tunnel has a capacity of 23 m^3/sec and it is planned for the entire aqueduct’s capacity to be increased to 23 m^3/sec during the next phase of Mornos aqueduct development. As a result the excess flows that Giona extension hydropower plant could exploit would rise from 3.5 m^3/sec for the current aqueduct capacity to 8.5 m^3/sec.

At the time of the study no available daily flow data were available in order to construct a flow duration curve for Giona location. Therefore the specific energy ε (KWh/m^3) of the proposed hydropower plant was estimated according to Equation 2:

$$\varepsilon = \frac{E}{V} = \frac{H_{net}}{367} \times n \qquad (2)$$

where:

H_{net}: the net elevation difference between Mornos reservoir water level and the hydropower plant (m)

n: turbine efficiency coefficient

E: Energy production (KWh)

V: Volume of water (m^3)

367: constant for unit version

For a value of H_{net} equal to 58 metres and an efficiency coefficient of 0.85 the specific energy of the proposed hydropower plant was estimated with a value of 0.1343 KWh/m^3. Based on average monthly flow data for the period 1995-2008 we get a rough estimation of potential average annual energy production of approximately 3.5 GWh.

However, in order to get more accurate estimations of the average annual energy production for Giona extension hydropower plant detailed calculations based on daily flow data are required in order to construct a flow duration curve for the particular location and to select an appropriate hydro turbine that will utilise the additional flow.

UWOT implementation

For the model implementation of the new proposed hydropower plant a new UWOT component was especially developed for this reason. The divergence (DV) component enables the splitting of the incoming signal into two outputs according to the value of the incoming signal. The implementation in UWOT followed the schematisation in Figure 9.12, where we have two serial DV components, the first separating the low flows (<7.5 m^3/sec) and sending them to Splitter 1 and the second one separating the high flows and sending the excess flow (>14.5 m^3/sec) to Splitter two and eventually Giona extension hydropower plant.

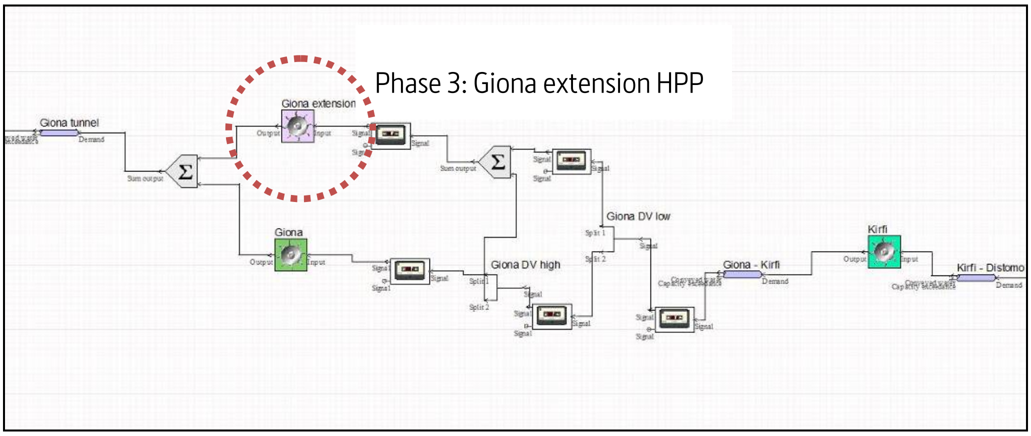


Figure 9.12. Detail of UWOT schematisation of the Athens hydrosystem – Giona extension HPP (Phase 3)

Model results

Figure 9.13 displays the average monthly energy consumption, as well as EYDAP's average monthly renewable energy production along the external water supply network, after the simulation of Phase 3 model. Once again these results do not include the solar power energy project and Psyttalia hydropower plant both included in Phase 2.

In comparison to the results of Phase 2 model there is no change in total energy consumption, as expected, since no energy saving measures were implemented at this stage either. The monthly pattern of renewable energy production is quite similar to the baseline, Phase 1 and Phase 2 scenario 2. However, a differentiation can be observed in the energy production during the month of July which has a bigger increase in its energy production in comparison to the rest of the months. This can be explained by the fact that Giona extension HPP in the model exploits the higher flows during the summer months and especially July which are left unexploited by the existing Giona HPP. Therefore the overall increase in energy production due to the addition of Giona extension HPP is not uniformly distributed to all of the months but it makes a bigger difference during the peak demand months (July) and the low demand months (November – February).

According to model estimations, after the implementation of Phase 3 interventions the average annual total energy consumption up to the water treatment plants remains the same at 87.46 GWh, the average annual energy production from EYDAP's hydropower plants increases to 27.94 GWh and the renewable energy fraction rises to 31.95 %.

As before the impact of the two additional interventions of Phase 2 that were not included in the model was taken into account only as an average annual value of estimated renewable energy production. Following the application of all interventions the average annual energy production from all EYDAP renewable energy sources is 33.24 GWh and the renewable energy fraction rises to 38.01 %.

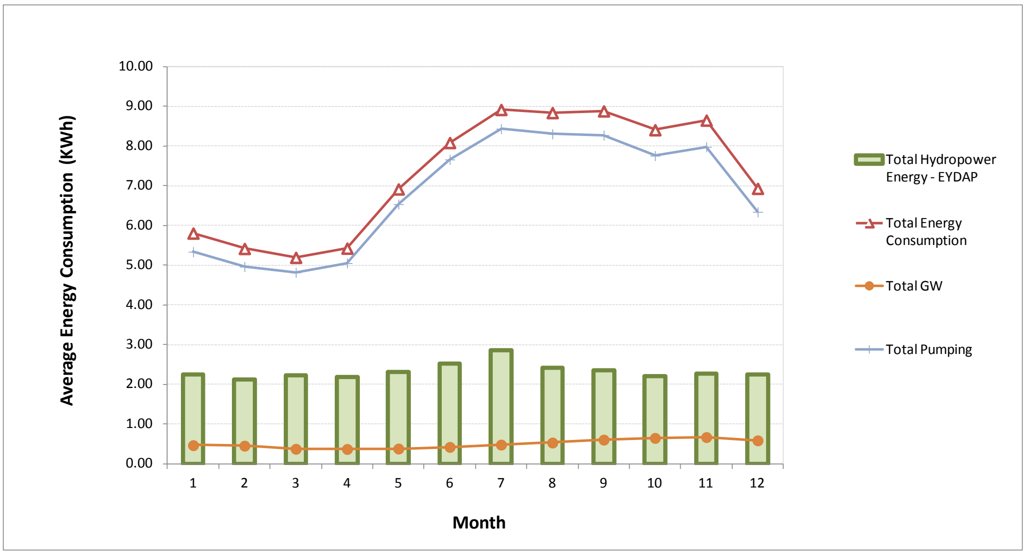


Figure 9.13: Average monthly energy consumption and production along the external water supply system - Phase 3

9.4.5 Phase 4 / Option A scenario – Analysis & Results

Set-up / Schematisation

Phase 4 includes the exploitation of the hydropower potential between Evinos and Mornos reservoirs; option A, the more conventional intervention, involves the development of a small hydropower plant at the outflow of Evinos – Mornos tunnel, whereas option B also includes the construction of a pump storage system between the two reservoirs. In this section the first option is examined.

The specific location has a significant energy production potential due to the elevation difference between the two reservoirs and the substantial volume of water transported from Evinos to Mornos reservoir, with an average annual value exceeding 200 hm^3 and in some years exceeding the value of 300 hm^3.

The annual hydropower energy production and turbine nominal power was estimated by the following set of equations:

$$h_f = \frac{v^2 n^2}{R^{4/3}} L \qquad (3)$$

$$P_d = 9.81 \times n_t \times Q_d \times h_d \qquad (4)$$

$$E = 9.81 \times n_t \times n_g \times n_{trans} \times \frac{V}{3600} \times h_d^{net} \qquad (5)$$

where:

h_f: (m) P_d: turbine efficiency coefficient

E: Energy production (KWh) L: Pipe length (m)

v: velocity (m/s) R: hydraulic radius (m)

V: Volume of water (m^3) h_d: Design head (m)

h_d^{net}: Net design head (m) Q_d: Design flow (m^3/s)

n_t: Turbine efficiency coefficient n_g: Generator efficiency coefficient

n_{trans}: Transformer efficiency coefficient

The design head was assumed equal to 58 metres corresponding to Evinos mean water level of 493 m. For transporting annually 300 hm^3 with a velocity of 1.5 m/sec the estimated nominal power of a Francis turbine is approximately 5.4 MW. The resulting annual energy production for the diversion of the same volume of water and for turbine efficiency coefficient of 0.90, calculated according to Francis turbine performance curves (U.S. Bureau of Reclamation, 1976), is approximately 28.5 GWh.

However for the purpose of this study a more conservative estimate of 20 GWh for the annual energy production was selected because: a) it will not be feasible to always operate the reservoir with a head equal to the design head, b) sometimes Evinos water level will result in a head smaller than the minimum allowed head for the turbine to operate and therefore some flows won't be exploited and c) sometimes higher velocities will be needed resulting to higher losses. The specific energy of the proposed hydropower plant at the outlet of Mornos – Evinos tunnel was calculated according to the estimated annual hydropower energy production for the diversion of 300 hm^3 of water.

UWOT implementation

The only difference in the Athens hydrosystem network in UWOT in comparison to the schematisation used for Phase 3 model is the addition of the new hydropower plant Evinos-Mornos (Figure 9.14). The hydro turbine (HD) component developed for the particular HPP is directly linked to Evinos Inflow timeseries which represents the inflow to Mornos from Evinos via the Evinos-Mornos tunnel. For the model implementation we have assumed the same average operation of Evinos - Mornos discharge as in historical data and we haven't introduced any special operational rules. Therefore most probably the model underestimates the average annual energy production from the particular HPP, since with modifications in the discharge operation rules we could achieve a higher energy production than just using the current "business as usual" operation. An interesting modification for future research work would be to simulate the hydrosystem as two distinct reservoirs, so that upstream and downstream reservoir levels are taken into account and the system operation is optimised to minimise the risk of failure and maximise hydropower energy generation.

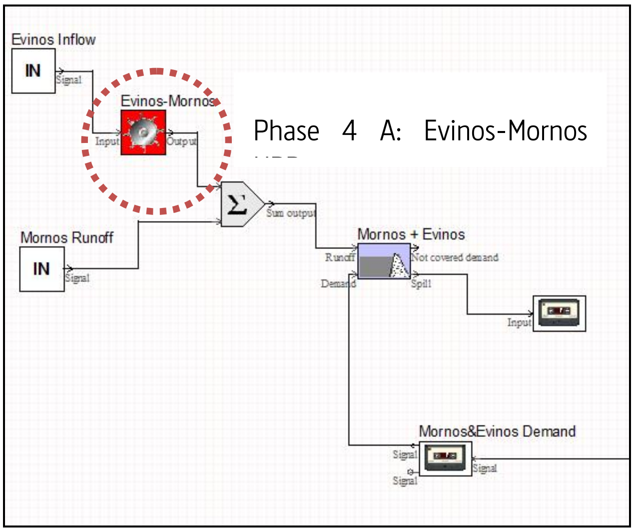


Figure 9.14: Detail of UWOT schematisation of the Athens hydrosystem – Evinos-Mornos HPP (Phase 4A)

Model results

Figure 9.15 displays the average monthly energy consumption, as well as EYDAP's average monthly renewable energy production along the external water supply network, after the simulation of Phase 4 / Option A model. Once again these results do not include the solar power energy project and Psyttalia hydropower plant both included in Phase 2.

In comparison to the results of phases 1 to 3 models there is no change in total energy consumption, as expected, since no energy saving measures were implemented at this stage either. However, in terms of renewable energy production there is a significant difference from the rest of the models both in the average annual value and the monthly pattern of the renewable energy generation. The significant amount of additional hydropower production resulting from the addition of Evinos-Mornos hydropower plant has a quite different monthly distribution to the rest of the hydropower plants of the external water supply system. Whereas most hydropower plants exhibit an increased energy production during the high water demand months (May – September), the particular hydropower plant is rather linked to water abstractions from Evinos to Mornos reservoirs. These abstractions are much higher during the winter months (November – April). Therefore the increase in hydropower production is most apparent during these months (Figure 9.15).

According to model estimations, after the implementation of Phase 4 / Option A interventions the average annual total energy consumption up to the water treatment plants remains the same at 87.46 GWh, the average annual energy production from EYDAP's hydropower plants increases to 41.75 GWh and the renewable energy fraction rises to 47.74 %.

As before the impact of the two additional interventions of Phase 2 that were not included in the model was taken into account only as an average annual value of estimated renewable energy production. Following the application of all interventions the average annual energy production from all EYDAP renewable energy sources is 47.05 GWh and the renewable energy fraction rises to 53.80 %.

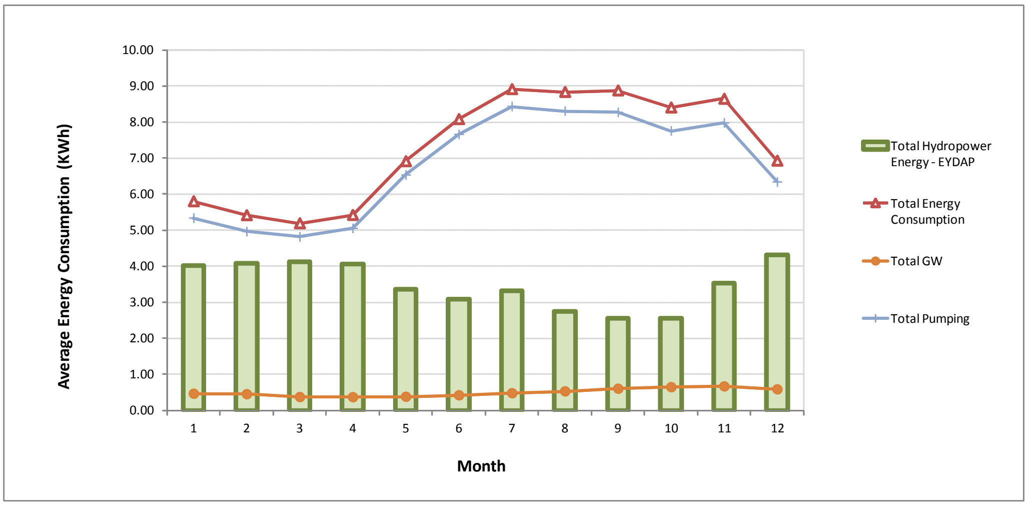


Figure 9.15: Average monthly energy consumption and production along the external water supply system - Phase 4A

9.4.6 Results Summary

The following table and graph present the summary results from all examined intervention phases and the corresponding UWOT models.

Table 9.7 includes values of average annual energy consumption up to the water treatment plants and all annual renewable energy production, as well as the renewable energy fraction for the baseline scenario and all intervention phases. The results presented include model outputs, but also annual estimates for the interventions that are not included in the modelling process.

Figure 9.16 displays the average monthly variation in energy consumption and hydropower energy production for the baseline scenario and the four intervention phases. The graph contains only results from the modelling process, therefore in terms of renewable energy generation it includes only the hydropower plants located on the Athens external water supply system.

Table 9.7. Summary results on average annual energy consumption and production on Athens UWC

	TOTAL ENERGY CONSUMPTION (PUMPING/GW) (GWh/y)	TOTAL EYDAP RENEWABLE ENERGY PRODUCTION (GWh/y)	TOTAL NET ENERGY CONSUMPTION (GWh/y)	RENEWABLE ENERGY FRACTION (%)
Baseline scenario	90.58 (84.57 / 6.00)	20.47	70.11	22.60
Phase 1	87.46 (81.45 / 6.00)	23.65	63.81	27.04
Phase 2	87.46 (81.45 / 6.00)	25.71 (31.01)*	61.75 (56.45)*	29.39 (35.45)*
Phase 3	87.46 (81.45 / 6.00)	27.94 (33.24)*	59.51 (54.21)*	31.95 (38.01)*
Phase 4 (Option A)	87.46 (81.45 / 6.00)	41.75 (47.05)*	45.71 (40.41)*	47.74 (53.80)*

**These are estimated results when the 2 interventions that were not included in the model (Psyttalia HHP and PV farm) are taken into account*

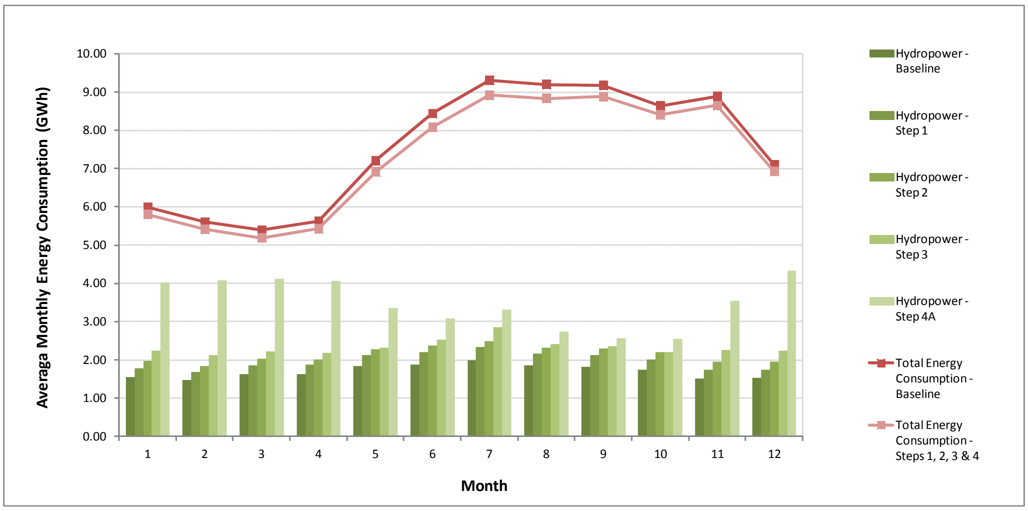


Figure 9.16. Summary graph of average monthly energy consumption and production along the external water supply system

9.4.7 Phase 4 / Option B scenario – Analysis & Results

Set-up / Schematisation

Option B of intervention Phase 4 builds upon Option A by adding a pump storage scheme between Evinos and Mornos reservoirs instead of including only the small hydropower plant at the outlet of Evinos – Mornos tunnel.

UWOT implementation

The analysis of the specific intervention was examined by developing a separate UWOT model than the one used for the other four intervention phases and baseline scenario. The new model uses a finer time step that is more appropriate for this type of application rather than using a monthly time step so that it will be able to capture the associated processes more accurately. The developed model, which could be considered as a modelling experiment for the initial assessment of the pump storage scheme, extends up to Giona location including the two parallel small hydropower plants, the existing Giona HPP and the proposed for Phase 3 Giona extension HPP (Figure 9.17).

Mornos and Evinos reservoirs are represented as in the previous models by a single "lumped" reservoir, but in this model an extra reservoir, *Evinos control*, has been added that represents the upper control reservoir used for solely the pump storage operation. *Evinos control* is a virtual reservoir that stores only the water from pump storage and doesn't receive the inflows of Evinos reservoir.

As in the model developed for Phase 4 / Option A Evinos inflow timeseries passes through the Evinos-Mornos hydropower plant before becoming inflow for the Evinos – Mornos lumped reservoir. In this case, a new inflow to the reservoir has been added that represents the extra inflow coming from the upper control reservoir, i.e. the water used for the pump-storage operation only. This inflow also produces an extra amount of renewable energy and the water amount transferred from the upper to the lower reservoir is controlled by the signal entering the pump component *Hydropower Plant*.

Regarding the demand signal of Mornos-Evinos reservoir besides the existing Athens water demand coming from Mornos main aqueduct, a new demand signal has been added. This demand refers to the water being pumped up from the lower to the upper reservoir via the pump component *Pump (Wind turbine)*. This demand signal and pump operation are controlled by the input timeseries entering the pump component.

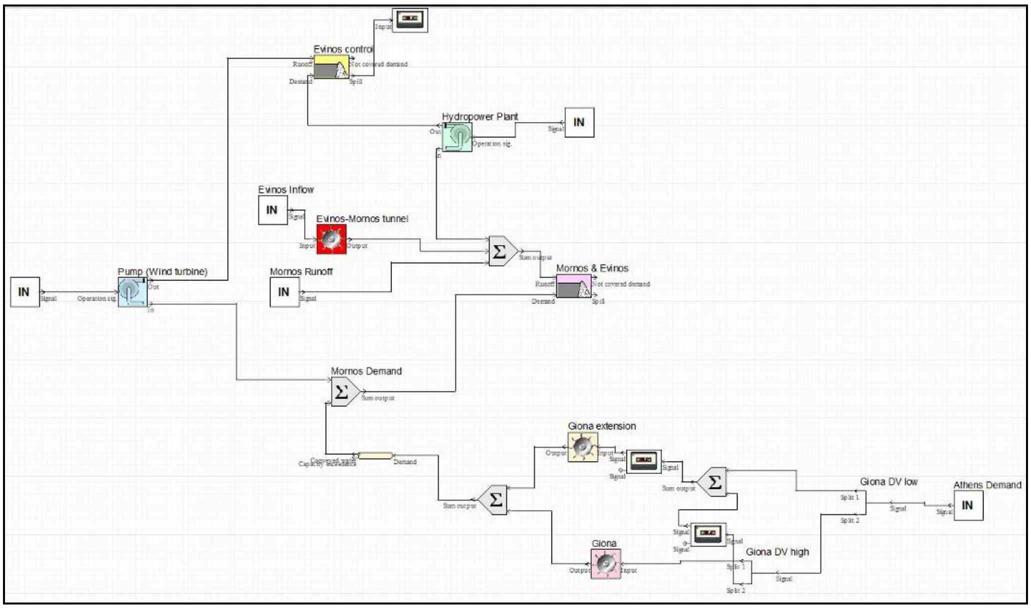


Figure 9.17: UWOT schematisation for the pump-storage scheme (Phase 4 / Option B)

The model was setup with a daily time step using historic data for the period 01/08/2002 to 24/01/2007. The input data used for the specific model have been defined as follows:

- For Evinos inflow that represents the inflow from Evinos to Mornos reservoir via the Evinos-Mornos a daily timeseries of reservoir outflow data was used from Mamassis et al. (2011).
- Mornos runoff daily timeseries was created from the corresponding monthly timeseries (from reservoir balance, Mamassis et al., 2011) by stochastic disaggregation using a uniform model.
- The daily demand signal at Giona location representing the Athens water supply demand was estimated from the average monthly demand of the model developed for the previous modelling scenarios that simulates the entire external water supply system.
- A daily timeseries of wind speed data from Mornos meteorological station was used for the assessment of the local wind energy potential (Mamassis et al., 2011).
- The daily wind velocity timeseries was converted to power output using an appropriate power curve (turbine efficiency) and this in turn was converted to daily generated energy. Using the available generated energy the daily volume of water pumped to the upper reservoir was calculated and used as the input signal for the pump operation.
- The creation of the input signal for the turbine operation was based on the daily flow timeseries of pumped water using a moving average.

Model results

Figure 9.18 displays separately the estimated average monthly energy production from the Evinos-Mornos small hydropower plant and the Evinos-Mornos pump-storage scheme as a result of the pump storage modelling experiment on the Athens external water supply network.

However, it should be noted that these results should be considered as indicative results of a preliminary modelling approach and assessment. It is suggested that the specific model needs further refinement in order to make a more accurate estimation of friction losses as a function of reservoir water level. For this purpose Mornos and Evinos reservoirs should be modelled as separate reservoirs and further appropriate modifications should be implemented within UWOT. Furthermore the entire Athens external hydrosystem should be put in a common modelling framework and run with a daily time step so that a direct comparison of all modelling scenarios is feasible.

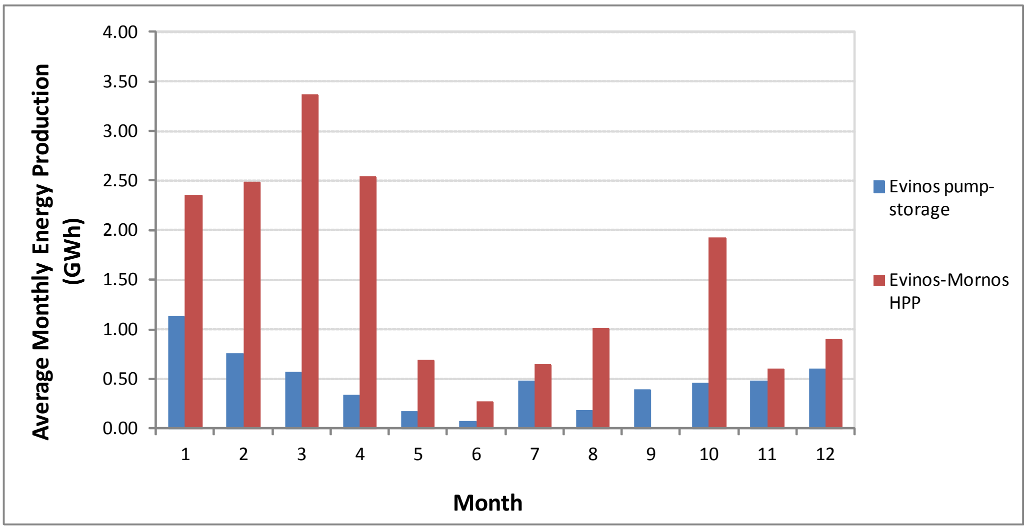


Figure 9.18. Average monthly energy production from Evinos-Mornos HPP and pump-storage scheme

Other considerations

The initial analysis has indicated that the pump storage option is feasible; however there are various technical and financial considerations that need to be taken into account and further explored:

- During the renewable scheme design special attention should be given to the fact that the pump operation does not intervene with the normal operation of the tunnel that is used for water supply purposes, which obviously has the highest priority.

- Since Mornos water level has a significant seasonal fluctuation a possible design solution for minimisation of the head for pumping would be the construction of a small control reservoir possibly at the outlet of Evinos-Mornos tunnel at the bottom of which the pump outlet will be located. The reservoir will always be the first to receive the diverted water from Evinos reservoir and the water will go to Mornos reservoir with overflow.
- Detailed analysis is needed for the selection of the most appropriate pump and turbine for the proposed scheme; either the selection of a combination of two separate units or a single reversible pump-turbine.
- The most significant issue for the proposed pump storage scheme is the relatively low elevation difference between the two reservoirs (the total head assuming Evinos mean water level is less than 60 metres) and the long horizontal length between them (30 km). This in effect means high friction losses and a relatively low hydropower production potential. A detailed analysis and modelling taking into account head variability and friction losses variability is therefore necessary.
- Due to high losses and low head it is presumed that pump storage with conventional fuels probably wouldn't be a financially attractive option. However, the combination with renewable energy sources seems more promising but a detailed cost benefit analysis is required to assess the financial feasibility of such an investment.

9.5 Proposed water-energy roadmap

The energy related intervention phases analysed in the previous sections were translated into steps of a possible water-energy Roadmap for the Athens urban water system. The information and results presented in this section present the first vision for the water-energy Roadmap, which currently focuses on the external water supply system of Athens.

Besides the research and modelling work carried out for the development of the presented scenarios and suggested interventions a series of meetings and workshops took place with representatives, upper management and senior engineers, of various departments of EYDAP. These were very informative as they resulted in gaining a better understanding of the major issues faced by the water company, the company's priorities, as well as communicating the work carried out for TRUST and identifying common areas of interest and ways forward.

Roadmap results and discussion

The *Renewable Energy Fraction* was estimated for the baseline scenario and all four intervention phases. It is defined as:

$$\text{Renewable Energy Fraction (\%)} = \frac{\text{Renewable Energy Generated}}{\text{Total Energy Consumed}}$$

Figure 9.19 presents the evolution of the *Renewable Energy Fraction* through all steps of the water-energy Athens Roadmap. This performance indicator could increase from the current value of 22.6% to as much as 53.8% for Step 4 of the Roadmap (Table 9.8).

Another measure estimated for the baseline scenario and all four intervention phases is the *Net Energy Consumption* of the Athens external urban water system. It is defined as:

$$\text{Net Energy Consumption (GWh/year)} = \text{Total Energy Consumption} - \text{Renewable Energy Production}$$

Figure 9.20 presents the evolution of the *Net Energy Consumption,* as well as the total energy consumption, through all steps of the water-energy Athens Roadmap. The value of this measure could decrease from the current value of 70.11 GWh/year to as much as 40.41 GWh/year for Step 4 of the Roadmap (Table 9.8).

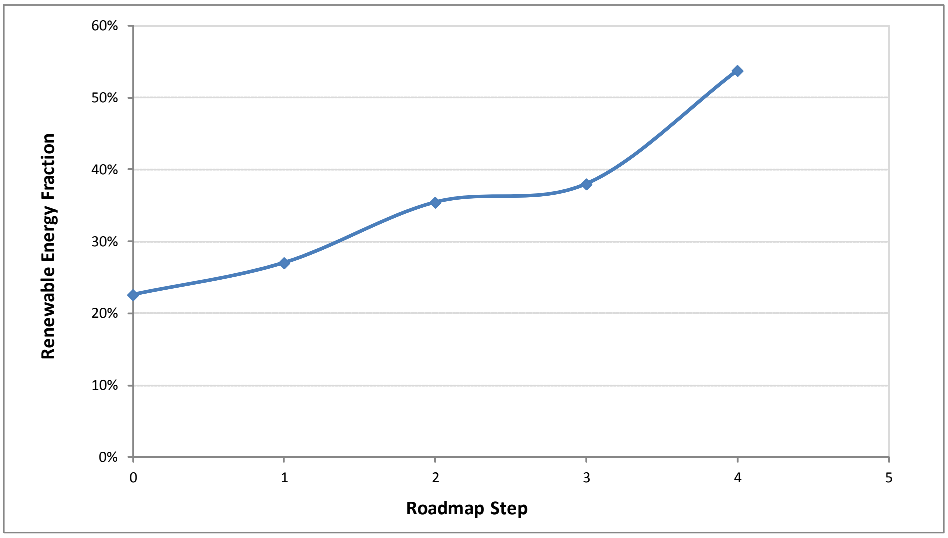


Figure 9.19: Evolution of renewable energy fraction for the water-energy Roadmap

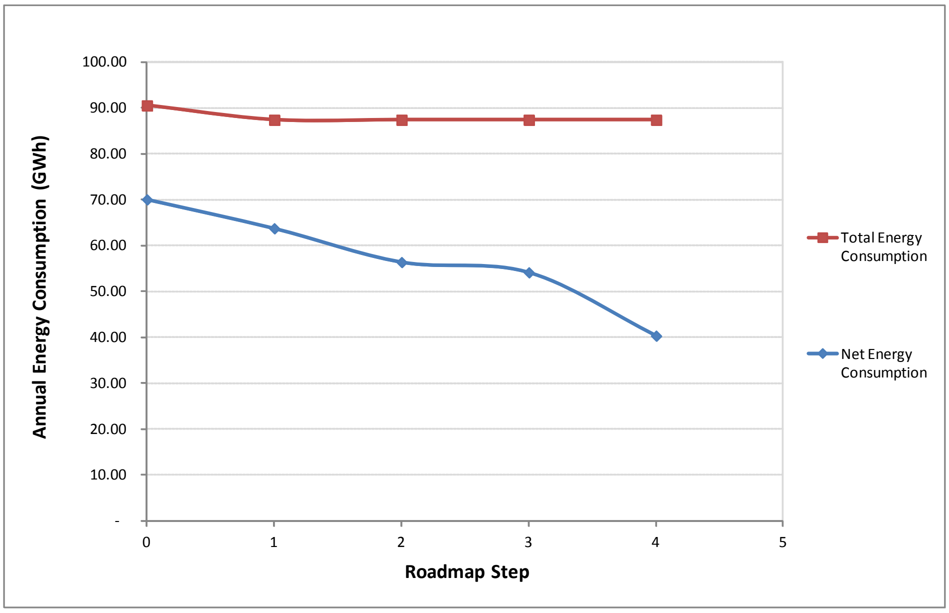


Figure 9.20: Evolution of net energy consumption for the water-energy roadmap

A final performance indicator employed for the evaluation of the proposed water-energy Roadmap is *Energy Intensity*, in this case of the external water supply system, which is defined as the energy consumption per unit volume of water delivered to the water treatment plants and expressed in KWh / m^3.

$$\text{Energy Intensity } (\text{KWh}/\text{m}^3) = \frac{\text{Energy consumption within the external UWS}}{\text{water delivered at WTPs}}$$

The graph presented in Figure 9.21 displays the evolution of *Energy Intensity* of the Athens external urban water system through all steps of the proposed water-energy Roadmap and refers to the water delivered to all four Athens water treatment plants. The red line indicates the energy intensity corresponding to the total energy consumption, while the blue line shows the energy intensity corresponding to the net energy consumption after taking into account the renewable energy production.

Furthermore, the various applied energy related interventions are indicated on the graph at the relevant Roadmap steps that they were applied. There are two different types of interventions, energy saving interventions, indicated with an orange arrow, and renewable energy interventions, indicated with a green arrow. It can be observed that only one energy-saving intervention was applied throughout the Roadmap, the pump replacement at Kiourka water treatment plant at Step 1. Therefore only at Step 1 of the Roadmap does the total energy intensity slightly decrease from its baseline value of 0.22 KWh / m^3 and then remains constant.

On the other hand, all the rest proposed interventions are renewable energy interventions and have an effect only on the net energy intensity, which apparently is quite significant. According to the results of the analysis the value of the specific indicator could decrease from the current value of 0.17 KWh / m^3 to as much as 0.10 KWh / m^3 for Step 4 of the Roadmap (Table 9.8).

It should be noted that the results of the pump-storage scheme have not been included in this graph or any other summary results since the particular modelling exercise was not carried out in a common modelling framework and therefore the specific results are not comparable with the model outputs of the rest of the analysis.

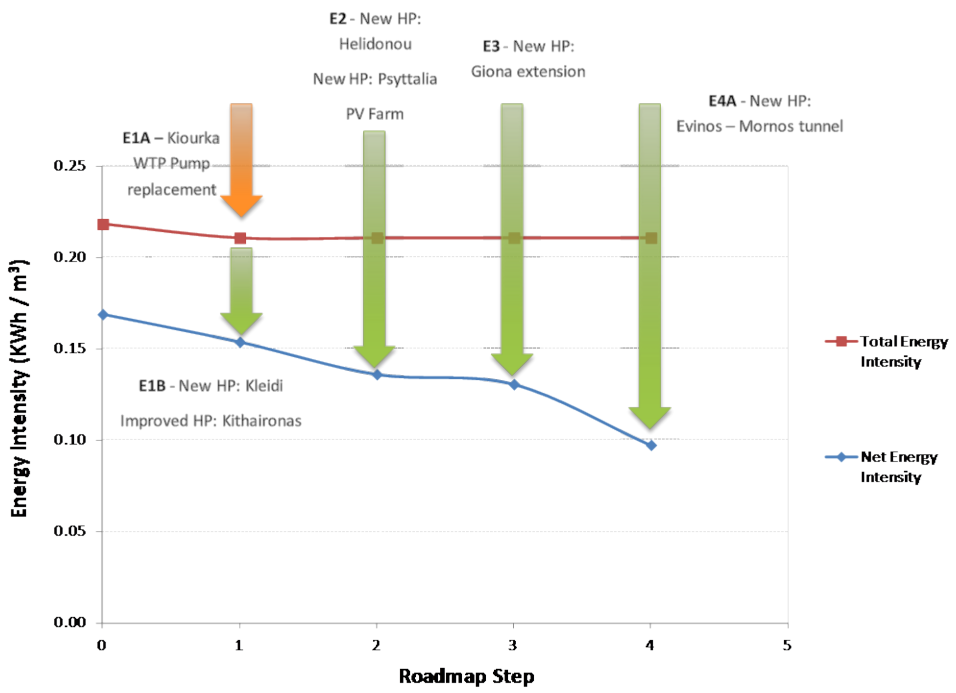


Figure 9.21. Evolution of energy intensity for the water-energy Roadmap

Table 9.8. Summary results on average annual energy consumption and production on Athens UWC

	NET ENERGY CONSUMPTION (KWH/m^3)	ENERGY INTENSITY (TOTAL / NET) (KWH/m^3)	RENEWABLE ENERGY FRACTION (%)
Baseline scenario	70.11	0.22 / 0.17	22.60
Roadmap Step 1	63.81	0.21 / 0.15	27.04
Roadmap Step 2	56.45	0.21 / 0.14	35.45
Roadmap Step 3	54.21	0.21 / 0.13	38.01
Roadmap Step 4	40.41	0.21 / 0.10	53.80

9.6 Discussion & conclusions

9.6.1 Discussion

Baseline model development

- The baseline model of the Athens external water supply network developed in UWOT showed an overall good performance in terms of simulating the water balance of the particularly complex urban water system of Athens. This fact indicates that the assumptions used were valid and model performance is not compromised.
- Similarly in terms of energy balance the model showed satisfactory behaviour in terms of simulating energy consumption, as well as energy production from the existing hydropower plants at the external water supply system. Energy production from the existing hydropower plants is the highest during the summer months when water demand is increased.

Identified energy related interventions

- The short term interventions included in Phases 1 and 2 are estimated to have a considerable impact on the net energy consumption and renewable energy fraction. Moreover, most of these interventions are quite straightforward since they already are in EYDAP's strategic plans.
- The development however of the photovoltaic park in Acharnes included in Phase 2 seems at this point quite uncertain. It is currently considered by EYDAP a risky investment mainly due to the unstable economic environment and especially due to the fact that the renewable electricity tariffs in the Greek market are no longer guaranteed.
- The preliminary analysis indicated that the extension of Giona small hydropower plant is probably a quite attractive technical option. Even though it is not currently in EYDAP's agenda, the implementation shouldn't require too much time and resources since a lot of infrastructure is already in place. Furthermore, the exploited flows by the new hydropower plant are expected to increase in the future if the capacity of Mornos aqueduct is to be increased. In order to get more accurate estimations of the average annual energy production by the specific hydropower plant more detailed analysis is required based on daily flow data and model simulation with daily time step. However, the development of this hydropower project will probably require high-level negotiations and cooperation between the two companies, PPC and EYDAP.
- From all interventions examined the development of the hydropower plant at the outlet of Evinos – Mornos tunnel seems to have the biggest impact on net energy consumption and renewable energy fraction. The specific location has a significant energy production potential due to the substantial volume of water transported from Evinos to Mornos reservoir and the elevation difference between the two reservoirs. The results indicate that contrary to most of the other hydropower plants, the Evinos – Mornos HPP has the highest renewable energy production during the winter months when the abstractions from Evinos to Mornos are increased. However, it should be noted that the analysis was carried out using current operation rules and therefore higher energy production could probably be achieved by optimising the Evinos-Mornos discharge operation rules. A more detailed technical analysis, as well as a financial feasibility study is required for more accurate estimations.
- The most significant disadvantage in the development of the pump storage scheme between Evinos and Mornos reservoirs is the relatively big longitudinal distance between the reservoirs in combination with the relatively low elevation difference between them, which results in high friction losses and a relatively low hydropower production potential. The development of such a scheme with conventional fuels probably wouldn't be a financially attractive option. The coupling with renewable energy sources such as wind power seems more promising but a detailed technical analysis with further refinement of the modelling approach, as well as a cost

benefit analysis are required to assess the technical and financial feasibility of such an investment.

9.6.2 Challenges & uncertainties

There are various potential challenges and uncertainties linked with the implementation of the identified energy related interventions and the proposed water energy Roadmap for the Athens urban water system; the most significant of which are:

- The complicated and time-consuming administrative, legislative and bureaucratic processes related to renewable energy sources development in Greece are very significant impediments for further exploitation and development by EYDAP. These processes are causing significant delays in the implementation of relevant projects.
- EYDAP has serious issues related with the guarding of renewable energy sources facilities and also difficulties are arising with the maintenance of such projects.
- An important barrier for the implementation of renewable energy sources projects and associated investments is the unstable economic environment and especially the fact that the renewable electricity tariffs are no longer guaranteed.

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10. MICRO-HYDRO GENERATION IN THE ALGARVE MULTI-MUNICIPAL WATER SUPPLY SYSTEM

10.1 Introduction

Small-scale hydro has long been recognized as an attractive form of renewable energy. Generating hydropower in a water supply system requires excess of pressure that cannot be saved upstream but can be recovered downstream. However, this type of solution is still under development, as it has not shown to be a cost-effective solution to apply in the water supply and wastewater systems. The main reasons are (i) that there are no turbines in the market for low flows and low head like the ones is this type of systems and (ii) that the variability of flows during the day (and consequently, the low heads, low efficiencies and low power produced), makes this solution not viable at least from the economical point of view.

The current chapter aims at describing of Águas do Algarve (AdA) water utility experience with micro-hydro power generation in urban water services, in particular in water supply systems, and carrying out a cost-benefit analysis of already implemented solutions.

10.2 Identification of micro–hydro generation solutions

Águas do Algarve S.A will very shortly reduce the emission of CO_2 into the atmosphere by about 1,129 tons/year. The initiative for the micro-production of green electricity from Algarve Multi-municipal Water Supply and Sanitation Systems is an addition to the main activity assigned to Águas do Algarve, S.A. and complies with the objectives that Portugal proposed to fulfil by signing the Kyoto Protocol.

One of the options for the micro-production of green electricity is the installation of micro-hydro plants in the water supply systems, which has the advantages of using system components that already exist (reservoirs, pipe lines, valves) and using a supply of a continuous and guaranteed flow along the day (Vieira and Ramos, 2008).

AdA has already several solutions implemented and planned to step-forward for hydro-energy production, namely:

(i) A micro-hydropower plant is already installed at the intake of the Beliche's Water Treatment Plant (WTP). This plant is currently operated and monitored as a pilot case study since the beginning of 2011. Installed power is about 16 kW and can be expanded to 24 kW.
(ii) A small hydropower plant with cross-flow turbine has been designed to be installed at Alcantarilha WTP.
(iii) Five design projects for new micro-hydro powerplants are concluded.
(iv) Twenty potential locations for the installation of new micro- hydro generation have been identified.

The present chapter will describe in more detail two of the hydro-energy production facilities, namely the Beliche micro-hydropower plant, which is already in operation, as well as the future Alcantarilha plant, to be installed in Alcantarilha WTP.

10.3 Beliche case study

10.3.1 General description

The water utility Águas do Algarve S.A. is composed of the Multi-Municipal Water Supply System (MMWSS) and the Multi-Municipal Waste Water System for the Algarve region. The MMWSS has 65 tanks, 450 km of pipes with diameter varying from 60 to 1,500 mm and four water sources:

- Odeleite/Beliche dam that delivers raw water to Tavira and Beliche WTP;
- Bravura dam delivering to Fontaínhas WTP;
- Odelouca dam delivering raw water to the Alcantarilha WTP.

The Odeleite and Beliche dams were constructed for creating a large reservoir for irrigation and water supply purposes. In 2008, it was installed a micro-hydropower plant at the upstream of Beliche WTP. Currently, the micro-hydropower plant has two turbines installed at an existing valve's chamber, in a bypass of the trunk main that supplies the WTP. The chamber and the bypass are prepared for the installation of a third turbine in the future.

The inlet discharge to the WTP is controlled by an automatic discharge control valve. There was a bypass to the normal circuit inside the valve chamber, which was adapted to receive the turbines. The turbines are pumps working as turbine (PAT) since the discharge can be controlled downstream by a specific control valve. In January of 2011, the hydropower station was connected to the national grid.

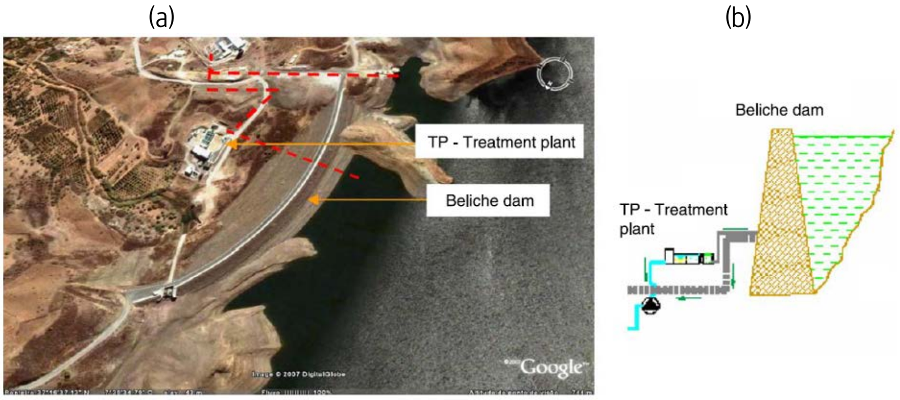


Figure 10.1. Beliche reservoir and micro-hydro powerplant:

(a) aerial view of Beliche dam and (b) hydraulic profile from the reservoir to the WTP

Figure 10.2: View of the bypass inside the valve chamber

Figure 10.3. View of the pump as turbine installation

10.3.2 Cost-benefit analysis

Turbine efficiency

A PAT is a hydraulic pump running in reverse so that, in combination with an induction generator, it recovers energy. It is a technology that has already been vastly explored and with proven results (Caxaria et al., 2011).

The main disadvantage of using PAT is the difficulty of finding the characteristics needed to select the correct pump for a particular site, which it is extremely important for the profitably of the installation (Ramos et al 2009). The ideal PAT design strategy involves the knowledge of flow and head patterns and the evaluation characteristic and efficiency curves (Carravetta et al. 2012, Fecarotta et al. 2013).

Therefore, even if the flow and head are considered daily constant, there is still a need to determine the characteristic curves of the PAT. The characteristic curves of low-head devices cannot be solely based on a large turbine scaling-down methodology and, in the case of PAT, the transformation from the operation as pump to the operation in reverse is not direct (Ramos et al. 2011). Both characteristic and efficiency curves can be obtained in three ways: experimentally, by computational fluid dynamics (CFD) and by any one-dimensional method (Carravetta et al. 2012).

Hence, prior to the installation of a micro-hydropower plant in the Beliche WTP, a set of experimental tests were carried out in the Tavira WTP to determine the PAT's main curves (characteristic curve and efficiency curve) and operating points. These tests were performed by Livramento, 2013 that describes, in detail, the adopted experimental protocols and the main obtained results which are summarized herein.

The nominal head in Beliche hydropower station is 16.3 m and the average flow rate is 96.2 l/s, which was approximated to the nominal flow. Due to the variability of flows, two PAT were installed with nominal flow-rates around 48 l/s. The installed turbo-machines were the KSB model ETANORM SYT 160 for 1750 rpm. The following figures show the technical characteristics of these pumps.

The experimental tests at Tavira WTP were carried out by creating physical and hydraulic conditions close to those verified in the Beliche WTP. The Beliche reservoir was simulated using a submersible pump (with 1.1 kW), controlled by a frequency converter, that elevated the water from a tank directly to the PAT to induce the nominal head-flow conditions. These tests were, consequently, limited by the maximum operating points of this submersible pump.

The first tests were performed with no pressure at the downstream end of the turbine and for different rotation frequencies. The obtained results are presented in Figure 10.4 and Figure 10.5.

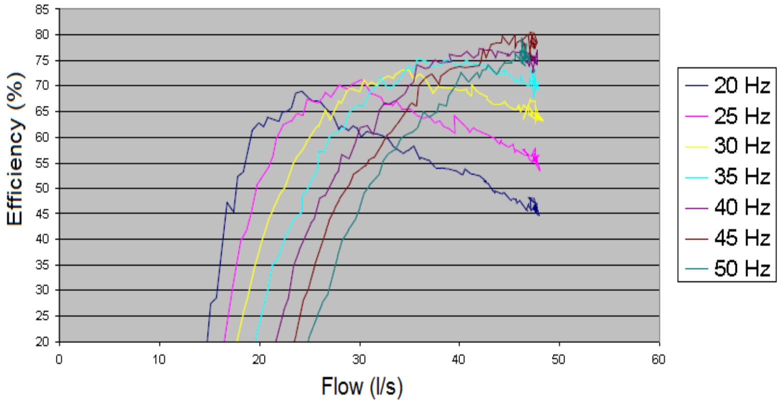


Figure 10.4: Efficiency curve for a no-pressure downstream condition (Livramento, 2013).

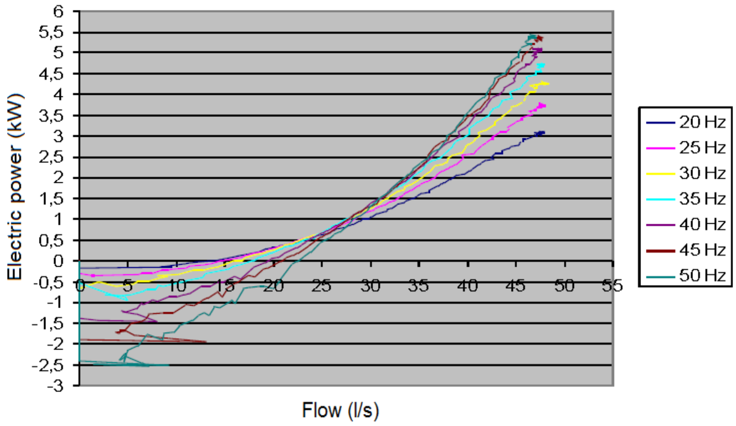


Figure 10.5. Electric power curve for a no pressure downstream condition

(Livramento, 2013).

The frequency that led to the best results was 50 Hz (Figure 10.5) which is also the national network frequency. Maximum values obtained for this frequency are presented in Table 10.1.

For the 50 Hz frequency, new tests were carried out with 3 m of pressure at downstream the turbine to simulate the height difference between the turbine and the outlet connected to the Beliche WTP. In these conditions, obtained results are presented in Figure 10.6a,b,c.

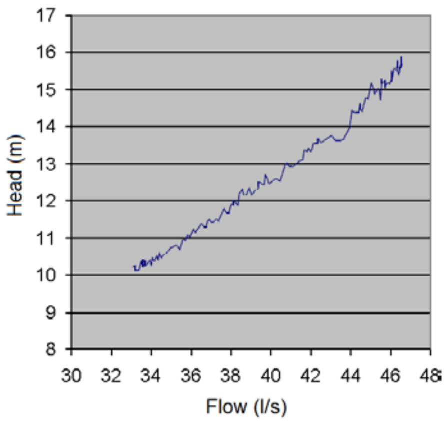
Tests were limited to 93% of the nominal flow and to 89% of the total available head in Beliche WTP. The torque in the turbine axis was also measured (Figure 10.6d).

Table 10.1. Maximum values for 1500 rpm (50 Hz) and no pressure downstream.

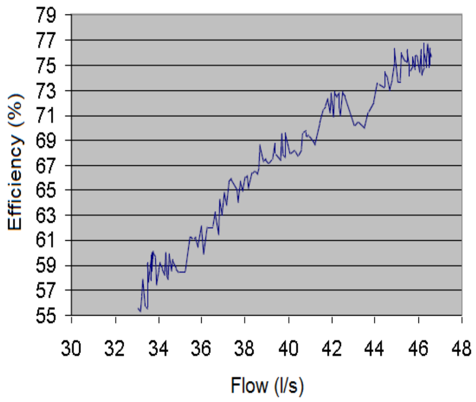
FLOW (l/s)	PRESSURE UPSTREAM (bar)	PRESSURE DOWNSTREAM (bar)	HEAD (m)	POWER (kW)	EFFICIENCY (%)
46.45	1.6	0	16	5.436	74.89

Table 10.2. Maximum values for 1500 rpm (50 Hz) and pressure downstream.

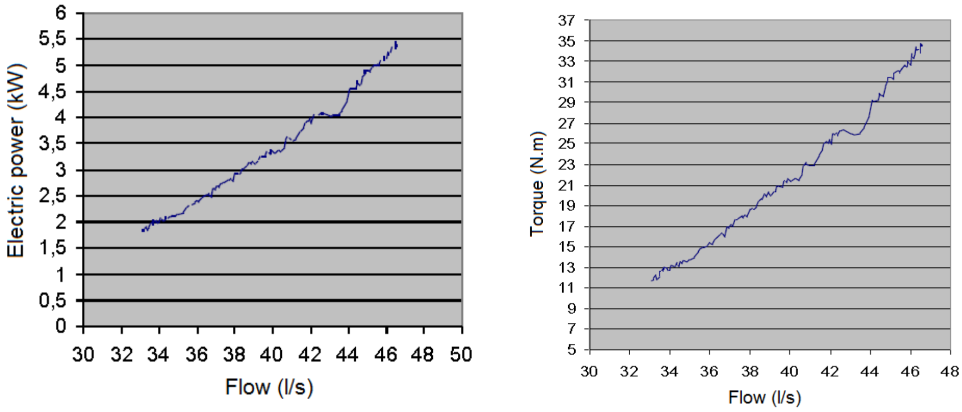
FLOW (l/s)	PRESSURE UPSTREAM (bar)	PRESSURE DOWNSTREAM (bar)	HEAD (m)	POWER (kW)	EFFICIENCY (%)
46.493	1.868	0.2986	15.69	5.428	76.37



(a) Characteristic curve of the turbine



(b) Efficiency curve for 1500 rpm (50 Hz) and pressure downstream



(c) electric power curve for 1500 rpm (50 Hz) and pressure downstream

(d) Torque in the turbine axis for 1500 rpm (50 Hz) and pressure downstream

Figure 10.6. Results of the experimental tests

(Livramento, 2013)

Energy production simulation

Two scenarios were considered for the estimation of the energy production:

- Scenario 1: production only during the high season;
- Scenario 2: production throughout the whole year.

The power of the turbo-machine is described by:

$$P = \eta\gamma Q H_u$$

where γ = the water specific weight (9800 N/m^3); H = turbine head H_u, calculated by the difference of the energy line between the upstream and downstream sections of the turbine; Q = the flow-rate (m^3/s); and η = the global turbomachine efficiency.

Since the WTP has worked only during part of the years 2011 and 2012, the daily flow series for the first scenario was obtained from the measurements of treated water volumes provided by Águas do Algarve. Figure 10.7 shows the variation of the daily flow during the years of 2011 and of 2012 as well as the average daily values for these two years. The turbines work, on average, 182 days per year, which corresponds approximately to 6 months.

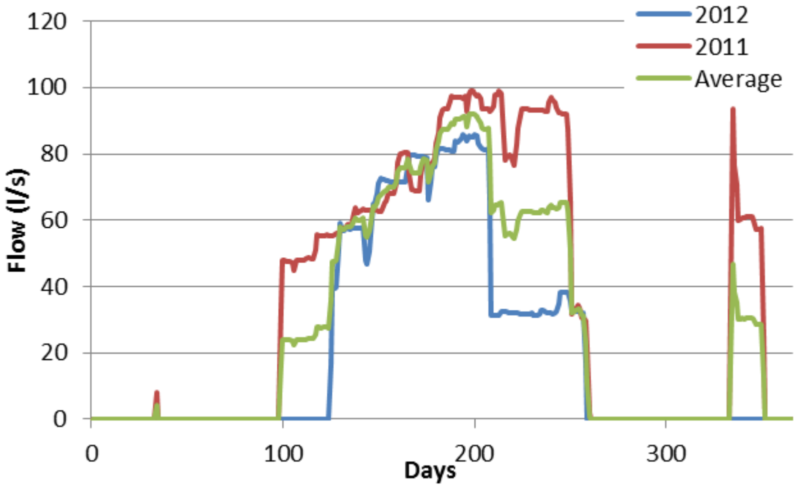


Figure 10.7:Daily flows in the Beliche WTP.

Since there were no available records of the water levels in the Beliche reservoir, an average head of 19 m was considered in the calculations.

Based on the tests performed in the Tavira WTP, a constant hydraulic efficiency of 74% was considered for the simulations. For the electric generator, it was assumed an electric efficiency of 90%. The total energy produced, for an average year, is around 28 784 kWh/year.

To estimate the energy produced in the second scenario with the turbine operating 365 days a year, a simple direct ratio was made, resulting in 57 726 kWh/year.

Economic analysis

To estimate the profitability of the hydropower station, two different compensation schemes were considered:

- micro-generation;
- consumption *in-situ*.

Since the Beliche hydropower plant is an installation for electricity production from a renewable energy source, based on a single production technology, and introduces less than 250 kWh in the national electric grid, it can have access to the Portuguese Mini-generation program. The production facility cannot produce nor inject in the national electric grid more than half of the contracted power consumption in order to be admitted in this program. Thus, the energy consumed in the WTP must be equal or greater than 50% of the energy produced.

The Portuguese Mini-generation program is defined in the Decree Law no. 34/2011, later regulated by the Ordinance no. 285/2011. This program allows two different compensatory schemes:

* the general scheme, in which the energy is valued according to the market conditions;
* the subsidized scheme, in which there is a reference rate, which was 250 €/MWh in 2011, whose value is annually reduced in 14%. There is also a fee to the reference price that depends on the technology. For hydropower, which is the current case, this fee is 50%.

The subsidized scheme has higher benefits and, therefore, was the one considered in the calculation of the income. If the project was licensed in 2011, the reference rate was 250 €/MWh. Therefore, the applicable rate is € 125 MW/h. This rate is valid for 15 years, switching for the general scheme at the end of this period.

For the *in-situ* consumption, the benefit was calculated from the average tariff value of purchase. From the data provided by the National Energy Services Regulatory Authority (ERSE - Entidade Reguladora dos Serviços Energéticos) concerning the transitional rate of the retail to final clients of medium voltage and assuming a long term use, an average rate of 118.9 €/MWh was estimated for 2011.

Given the lack of information, the initial costs were estimated with resort to the study by Ramos and Ramos, 2010. The cost of the equipment for a hydroelectric plant varies nonlinearly with the installed power and Ramos and Ramos, 2010 present an estimate of this variability for water turbines and for PAT – Figure 10.8.

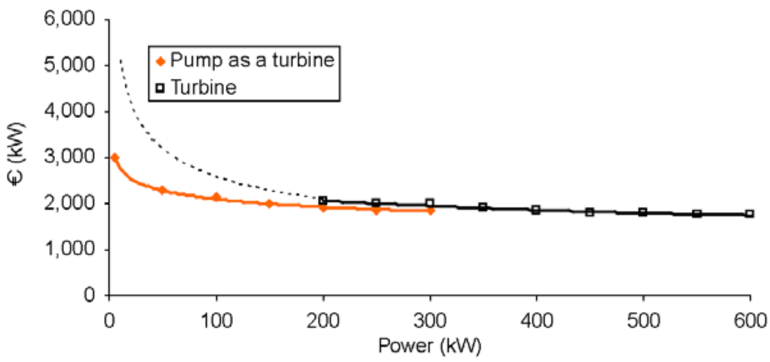


Figure 10.8. Curves for the hydropower equipment initial cost

(Ramos and Ramos, 2010).

The PAT are noticeably less expensive than water turbines, as pumps are mass-produced, with lower costs when compared with turbines – Figure 10.9.

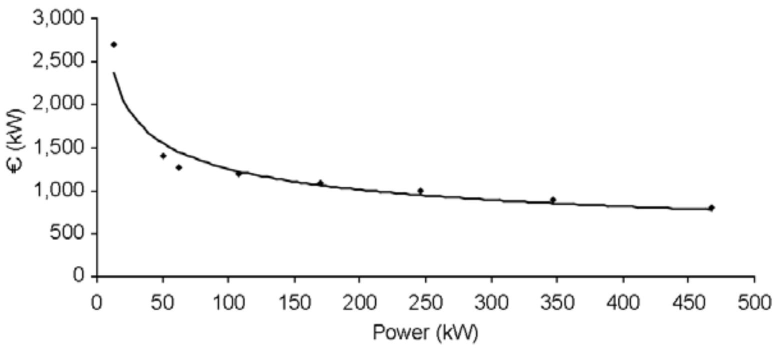


Figure 10.9. Water pumps initial cost

(Ramos and Ramos 2010).

In view of the fact that the hydroelectric equipment was installed in an already existing valve chamber, implying that heavy civil works were not necessary, the cost was estimated in around € 30,000.

The economic analysis was based on constant prices, assuming different discount rates, for a period of 15 years.

It was considered 2% of the total cost for maintenance during this period.

The Net Present Value (NPV) and the Benefit-cost ratio (BCR) were calculated for three different discount rates (2, 4 and 6%) and the Internal Rate of Return (IRR) was determined for the 15 years period.

Results for the first energy production scenario (production only during the high season) are presented in Table 10.3, and for the second scenario (production throughout the year) in Table10.4.

Table 10.3. Economic analysis for the first scenario.

REMUNERATION	MICRO-GENERATION			CONSUMPTION IN-SITU		
Discount rate	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%
NPV (€)	15 323	8 537	2 911	13 078	6 594	1 214
BCR	1.50	1.27	1.09	1.43	1.21	1.04
IRR	7.2%			6.5%		

Table 10.4. Economic analysis for the second scenario.

REMUNERATION	MICRO-GENERATION			CONSUMPTION IN-SITU		
Discount rate	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%
NPV (€)	61 808	48 760	38 048	57 306	44 846	36 644
BCR	3.02	2.56	2.20	2.87	2.44	2.09
IRR	18.7%			17.7%		

In Figure 10.10 and Figure 10.11 the two scenarios are compared for the different types of remuneration. It becomes clear that the period of operation is a very important parameter for the profitability of the installation.

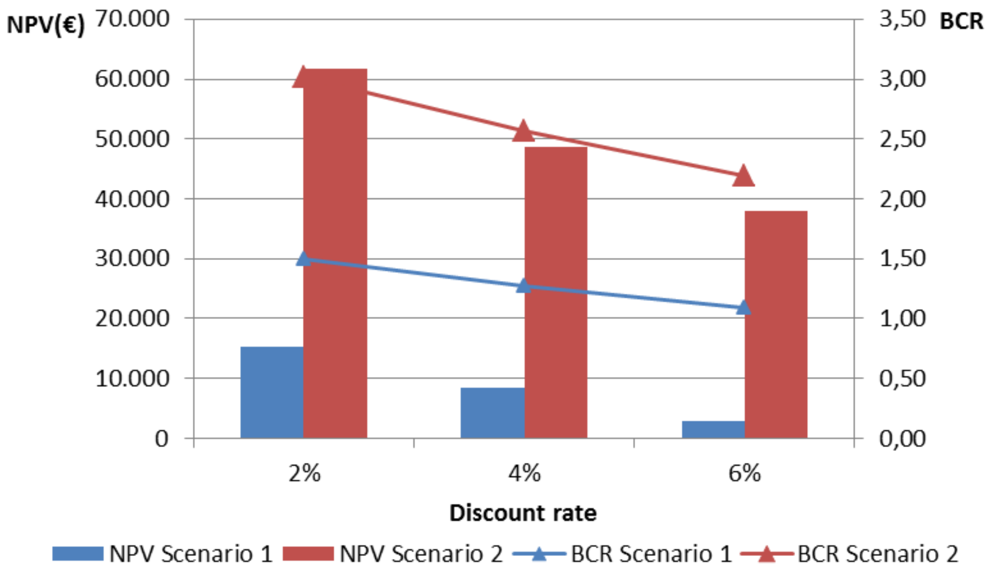


Figure 10.10. NPV and BCR for remuneration with micro-production.

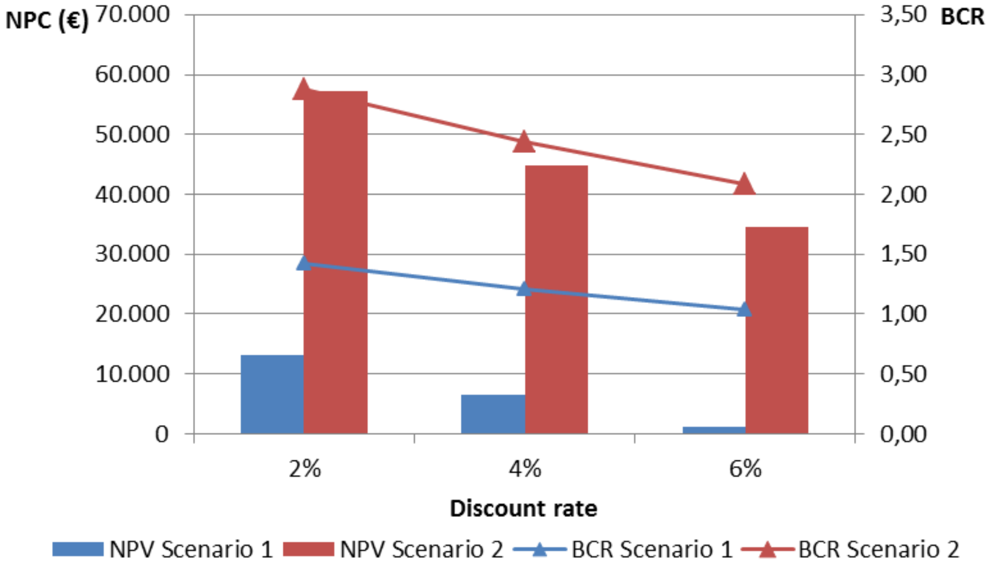


Figure 10.11. NPV and BCR for remuneration with consumption in-situ.

Since the capital costs for the installation of the equipment were estimated, calculations were repeated for higher and lower values, namely for 40 000 € and for 30 000 €.

From these results, it can be concluded that the revenue of the project depends strongly on the capital costs.

From the analysis of these results, we can conclude that, while the first scenario presents low NPV, the second scenario has good chances of being lucrative. In fact, the second scenario has positive results for all three hypothetical capital costs and for both types of remuneration.

It can also be verified that the remuneration in micro-generation is more advantageous than the consumption in-situ.

The analysis carried out has several assumptions associated being one of the most relevant assuming a constant flow, head and efficiency during the day. In practice, flow rates vary during the day which has a direct impact on generated power.

Additionally, the only O&M costs considered were the ones associated to the hydro-power plant; O&M of Beliche and Tavira WTP have been neglected. AdA claims that, when these costs are taken into account, the operation of the hydropower plant is not viable, as O&M cots of Beliche WTP are almost five times the ones of Tavira WTP. In this context, other than economical dimensions of analysis should be considered, such as the risk, the performance and the use of renewable energy sources.

Table 10.5. Economic analysis for a higher investment cost (40,000 €) and for the first scenario.

REMUNERATION	MICRO-GENERATION			CONSUMPTION IN-SITU		
Discount rate	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%
NPV (€)	5 020	-1 952	-7 766	2 775	-3 895	-9 463
BCR	1.12	0.95	0.82	1.07	0.91	0.78
IRR	3.4%			2.8%		

Table 10.6. Economic analysis for a higher investment cost (40,000 €) and for the second scenario.

REMUNERATION	MICRO-GENERATION			CONSUMPTION IN-SITU		
Discount rate	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%
NPV (€)	51 506	38 272	27 370	47 003	34 375	23 967
BCR	2.26	1.92	1.65	2.15	1.83	1.57
IRR	13.4%			12.6%		

Table 10.7. Economic analysis for a lower investment cost (30,000 €) and for the first scenario.

REMUNERATION	MICRO-GENERATION			CONSUMPTION IN-SITU		
Discount rate	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%
NPV (€)	25 626	19 026	13 589	23 381	17 083	11 892
BCR	2.26	1.91	1.64	2.15	1.82	1.56
IRR	13.4%			12.6%		

Table 10.8. Economic analysis for a lower investment cost (30,000 €) and for the second scenario.

REMUNERATION	MICRO-GENERATION			CONSUMPTION IN-SITU		
Discount rate	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%
NPV (€)	72 111	59 249	48 726	23 381	17 083	11 892
BCR	4.53	3.85	3.30	4.31	3.66	3.14
IRR	27.5%			26.3%		

10.3.3 Energy production for variable flow demand

Simulation model

The previous analysis not only assumed a constant flow, head and efficiency during the day, but also considered that the turbinated flow is the same as the demand downstream the Beliche WTP.

To add more sensibility to the weight of these assumptions in the calculations of the produced energy, simulations were performed in the hydraulic software Bentley's WaterGEMS©. Figure 10.12 shows the scheme used to model the Beliche Power plant system.

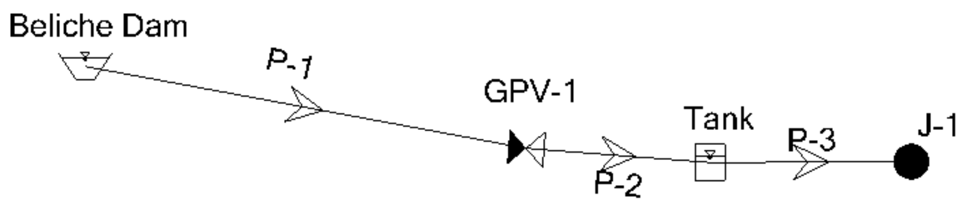


Figure 10.12. Scheme of Beliche Power plant system used in the WaterGEMS© model.

The Beliche dam was considered as a reservoir with an elevation of 44.6 m, from which the water is conveyed to the micro-hydro power plant by a concrete pipe. The micro-hydro power plant, and consequently, the two PAT, are represented by a general purpose valve (GPV-1) installed at elevation 21.3m and its head-loss curve is admitted to be equal to the characteristic curve of the turbine. Downstream of the micro-hydro powerplant, and admitting that the head-loss is negligible between these two elements, there is a tank with an initial elevation of 24.3 m which represents the Beliche WTP.

¡Error! No se encuentra el origen de la referencia.10.13 shows the used characteristic curve for the combination of both PAT, which was adapted from the one obtained by Livramento, 2013). It was assumed that the consumption of water in the system is imposed by the demand junction (J-1) and varies during the day as shown in Figure 10.14.

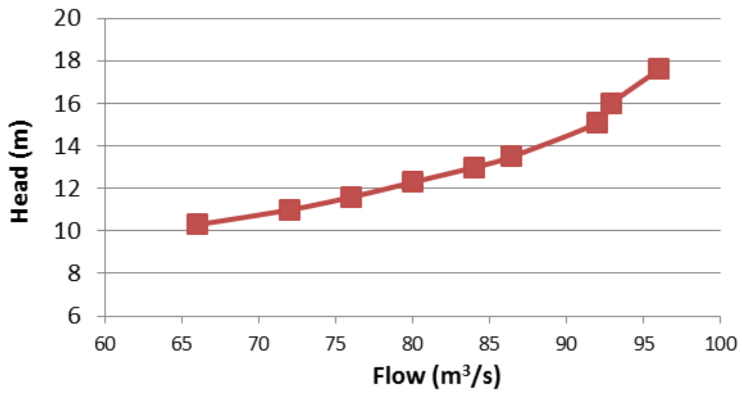


Figure 10.13. Characteristic curve of the set of two turbines adapted from Livramento, 2013.

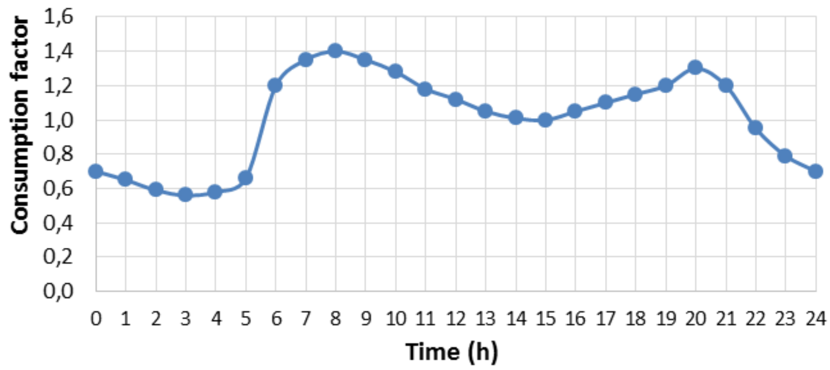


Figure 10.14. Daily water consumption factors considered in the analysis downstream of Beliche WTP.

Simulation results

Once again, two scenarios were considered for the estimation of the energy production:

- Scenario 1: production only during the high season (182 days);
- Scenario 2: production throughout the whole year.

As the average daily flow in May 2011 is very close to the average daily flow in the 182 days of operation, this month was considered as a representative month of the year.

As an initial setting, it was admitted the nonexistence of regulation in the WTP (the element Tank was removed from the scheme), allowing the variation in the demand to have a direct effect on the turbine operation. Thus, the flow in the turbine, in each hour, reaches the same value as the flow leaving the WTP, epresented by the junction J-1. The power was calculated for the representative month (May 2011) and the results of the initial simulation are shown in Table 10.9.

Table 10.9. Results obtained in the WaterGEMS© model without the Tank representing the WTP.

TIME (HOURS)	GPV-1 FLOW (L/S)	GPV-1 – HEAD-LOSS (NET HEAD) (m)	J-1 DEMAND (L/S)	η (%)	P (KW)
00:00	41.9	7.5	41.9	71.4	2.2
01:00	38.5	7.1	38.5	66.6	1.8
02:00	35.7	6.8	35.7	61.6	1.5
03:00	35.4	6.7	35.4	61.1	1.4
04:00	38.5	7.1	38.5	66.6	1.8
05:00	57.7	9.3	57.7	79.6	4.2
06:00	79.1	12.1	79.1	67.9	6.4
07:00	85.3	13.3	85.3	72.0	8.0
08:00	85.3	13.3	85.3	72.0	8.0
09:00	81.6	12.6	81.6	69.7	7.0
10:00	76.3	11.7	76.3	66.2	5.8
11:00	71.4	10.9	71.4	61.6	4.7
12:00	67.3	10.5	67.3	57.6	4.0
13:00	63.9	10.1	63.9	54.0	3.4
14:00	62.4	9.9	62.4	54.0	3.3
15:00	63.6	10.0	63.6	54.0	3.4
16:00	66.7	10.4	66.7	56.4	3.8
17:00	69.8	10.7	69.8	60.4	4.4
18:00	72.9	11.1	72.9	62.9	5.0
19:00	77.6	11.9	77.6	78.2	7.1
20:00	77.6	11.9	77.6	78.2	7.1
21:00	66.7	10.4	66.7	56.4	3.8
22:00	54	8.9	54	79.6	3.8
23:00	46.2	8.0	46.2	76.2	2.8
24:00	41.9	7.5	41.9	71.4	2.2

The results show a significant variation in the flow and head in the turbine. As the operation of both turbines at the same time starts for flows around 50 l/s, it can be observed that between 22:00 and 04:00 only one PAT operates.

This simulation results in 107 kWh/day for the month of May 2011. Considering that this value is representative of the average daily energy production:

- Scenario 1: 19 458 kWh/year of energy production;
- Scenario 2: 39 019 kWh/year of energy production.

The simulation was repeated, now considering the existence of the Tank. As there is a regulation inside the WTP, the turbines are not directly affected by the variations in the demand and the turbinated flow is more stable.

The results obtained with simulation in the WaterGEMS© model considering the average daily flow in May 2011 and the presence of a regulating tank are presented in Table 10.10, as well as the calculation of the produced power.

Table 10.10. Results obtained in the WaterGEMS© model with the Tank representing the WTP.

TIME (HOURS)	TANK - LEVEL (M)	TANK - PERCENT FULL (%)	GPV-1 FLOW (L/S)	GPV-1 – HEAD-LOSS (NET HEAD) (M)	J-1 DEMAND (L/S)	H(%)	P (KW)
00:00	23.3	71.7	94.6	17.7	41.9	76.9	12.6
01:00	23.4	73.3	94.5	17.6	38.5	76.9	12.5
02:00	23.5	75.0	94.4	17.5	35.7	76.9	12.4
03:00	23.6	76.8	94.3	17.4	35.4	76.9	12.3
04:00	23.7	78.6	94.2	17.3	38.5	76.8	12.3
05:00	23.8	80.3	94.1	17.2	57.7	76.8	12.2
06:00	23.9	81.4	94.0	17.1	79.1	76.8	12.1
07:00	23.9	81.9	94.0	17.1	85.3	76.8	12.1
08:00	23.9	82.1	94.0	17.1	85.3	76.8	12.1
09:00	23.9	82.4	94.0	17.1	81.6	76.8	12.1
10:00	24.0	82.8	93.9	17.0	76.3	76.8	12.0
11:00	24.0	83.3	93.9	17.0	71.4	76.8	12.0
12:00	24.0	84.0	93.9	17.0	67.3	76.8	12.0
13:00	24.1	84.8	93.8	16.9	63.9	76.7	11.9
14:00	24.1	85.7	93.8	16.9	62.4	76.7	11.9
15:00	24.2	86.7	93.7	16.8	63.6	76.7	11.8
16:00	24.3	87.6	93.7	16.8	66.7	76.7	11.8
17:00	24.3	88.4	93.6	16.7	69.8	76.6	11.7
18:00	24.4	89.1	93.6	16.7	72.9	76.6	11.7
19:00	24.4	89.8	93.5	16.6	77.6	76.6	11.7
20:00	24.4	90.3	93.5	16.6	77.6	76.6	11.7
21:00	24.4	90.7	93.5	16.6	66.7	76.6	11.6
22:00	24.5	91.6	93.4	16.5	54	76.6	11.6
23:00	24.6	92.8	93.4	16.5	46.2	76.6	11.5
24:00	24.7	94.2	93.3	16.4	41.9	76.5	11.5

This simulation results in 299 kWh/day in the month of May 2011. Considering that this value is representative of the average daily energy production:

- Scenario 1: 54 436 kWh/year of energy production;
- Scenario 2: 109 172 kWh/year of energy production.

Sensitivity Analysis

In the analysis of energy production with the regularization tank, it was imposed a variable demand at junction J-1, downstream of the WTP. Despite these demand variations throughout the day, the values of the turbinated flow remain approximately constant and at the design flow, 96 l/s, because the WTP represented by the Tank element allows the regulation according to its storage capacity.

The head values do not suffer significant variations either. However, there are slight changes, which are related to the difference in the head between the operations with one or both turbines. These variations are shown in Figure 10.15

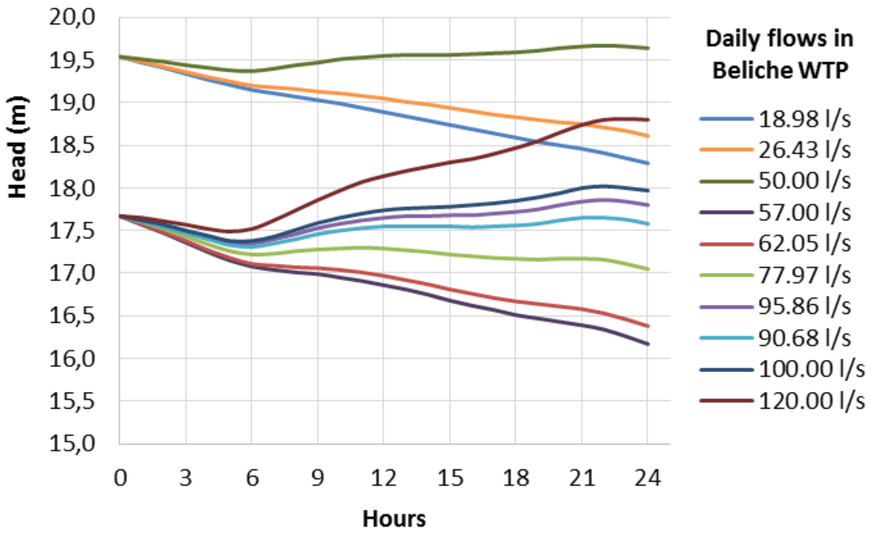


Figure 10.15. Variation of the head in the turbine (or group of 2 turbines) as a function of the demand in junction J-1.

Regarding the water levels inside the regularization tank, there is a daily variation (Figure 10.16).

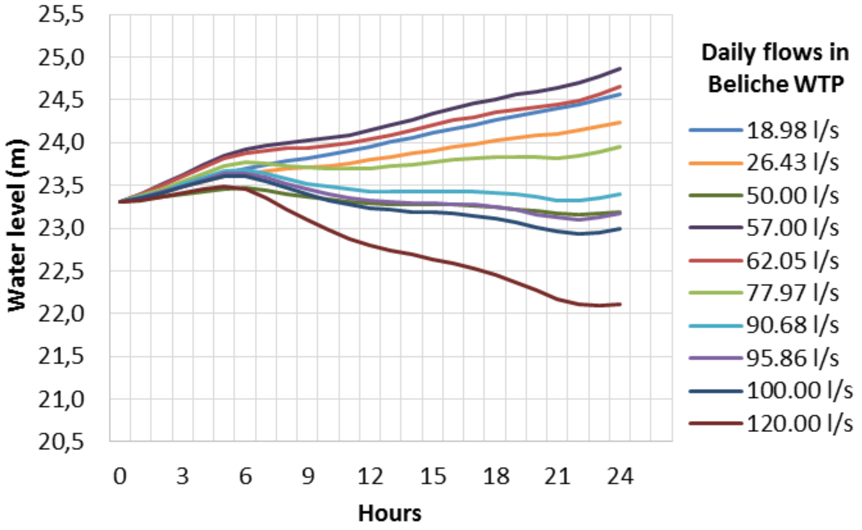


Figure 10.16. Variation of the water level in the regularization tank as function of the demand in node J-1.

From the observation of Figure 10.17, it is visible an increase in energy produced with the increase of water consumption (in agreement with load energy and water consumption diagrams).

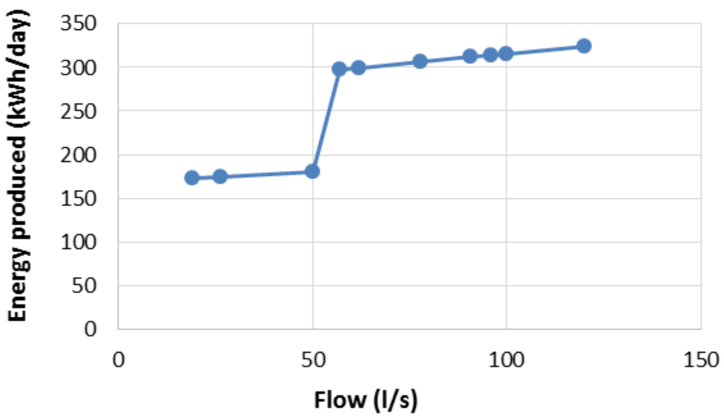


Figure 10.17. Daily energy production, with regularization at the WTP, due to the demand in node J-1.

In the analysis without the regularization tank, the variations of both flow and turbine head were significant, as shown in Figure 10.18 and Figure 10.19. This fact explains the different values of energy produced.

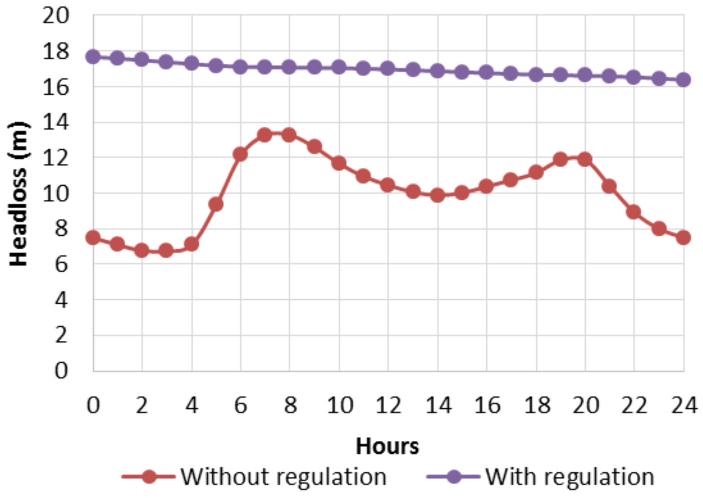


Figure 10.18. Comparison of the turbine head throughout the day with and without regulation, for the reference month.

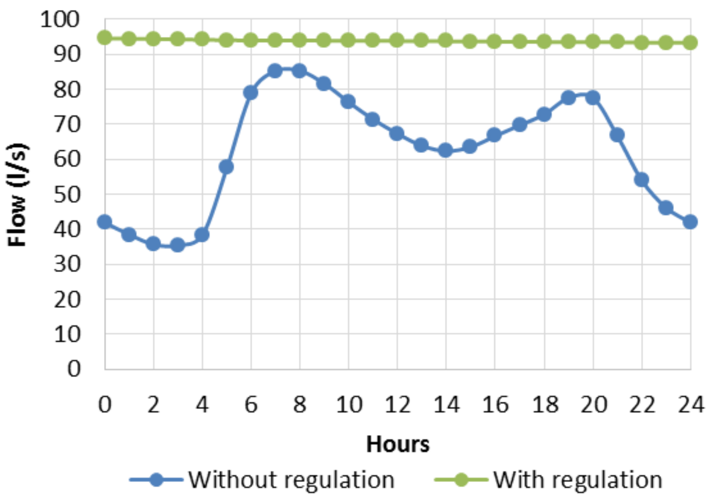


Figure 10.19. Comparison of the turbinated flow throughout the day with and without regulation, for the reference month.

Results discussion

The values of energy production obtained in the simulations with WaterGEMS© differ significantly from the ones previously obtained, as can be seen in Table 10.11. These differences come from the assumption of an average reference demand variation, in one case, and from the consideration of a volume regulation that allows the turbines to operate at the best efficiency point, in the second case.

Table 10.11. Annual energy production obtained with different types of simulation.

TYPE OF SIMULATION	SCENARIO	MWh/year
Daily flows analisys	1	29
	2	58
WaterGEMS©, without the regulation	1	19
	2	39
WaterGEMS©, with the regulation	1	54
	2	109

It can be concluded that if there is a variation in demand, the turbinated flow and corresponding head will vary throughout the day, negatively affecting the energy production. Nevertheless, if there is a regulation of the flow, this variation does not have an impact in the energy production and the turbines are able to constantly operate at their best efficiency points.

10.3.4 Regulation for variable flow conditions

As it has been concluded in the previous analysis, in case of a variable flow demand, the variations of turbinated flow and head will have a negative impact in the efficiency of the turbines and, consequently, in the energy production.

If the downstream reservoir has storage capacity to face the variability of the demand, allowing a constant operation in the upstream turbine, with constant flow, head and efficiency, the system may not suffer the effects of changes in the demand.

However, there are other types of flow control that can be considered when this volume regulation is not possible. Carravetta et al., 2012 proposed a method, called variable operating strategy (VOS), to select the appropriate PAT for a given location. This strategy implies a regulation, which can be obtained with two different methods: hydraulic regulation and electric regulation.

The hydraulic regulation is done through the operation of two valves installed as in Figure 10.20. When the available head is higher than the machine's maximum head-drop, the series valve dissipates the excess pressure. When the discharge is larger and the PAT produces a head-drop higher than the available head, the bypass is opened.

In the electric regulation a variable speed operation is used. The angular velocity of the runner is changed by varying the frequency of the electric signal by using an inverter to match the load conditions. Nevertheless, if the energy is to be injected in the national grid, it implies the need for a frequency converter to adjust to the network.

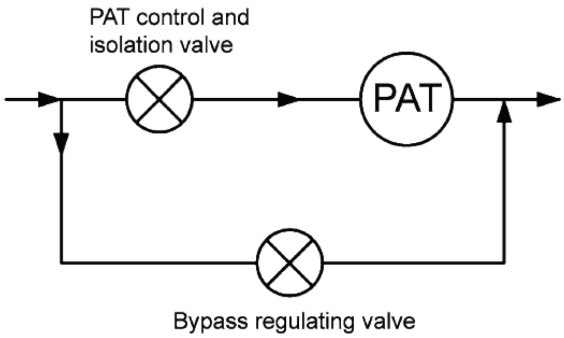


Figure 10.20. Installation scheme for the hydraulic regulation (Carravetta et al., 2012).

10.4 Alcantarilha case study

10.4.1 General overview

Alcantarilha WTP has a maximum treatment capacity of 259 000 m^3/day, corresponding to an equivalent population of 620 000 inhabitantes. The treatment capacity is distributed by 3 treatment lines in order to better respond to seasonal variability of flows.

Alcantarilha WTP receives raw water from Funcho reservoir and also from two ground water sources, Vale da Vila and Benaciate. It can also receive water from Odelouca reservoir. Water admission to Alcantarilha WTP is achieved through a gravity water main with 2.5 m diameter and approximately 12 km in length.

The total energy consumption of Alcantarilha WTP in 2011 was of 6,9 GWh, with a cost of 560 k€ and representing the consumption of 592,14 tonne of oil equivalent. Considering the fact that the main facilities of the company required a total electricity consumption of 48,6 GWh, the energy consumption in Alcantarilha WTP represents about 14% of the total energy consumption of Águas do Algarve. And approximately 13% of the total energy costs.

Consumption varies greatly throughout the year due to the strong increase in seasonal population, with peak during summer months (July through September). Figure 10.21 presents the monthly energy consumption in Alcantarilha WTP in 2011, with a minimum of 0.35 GWh in March and a maximum more than 2.5 times this value, of 0.92 GWh, in August.

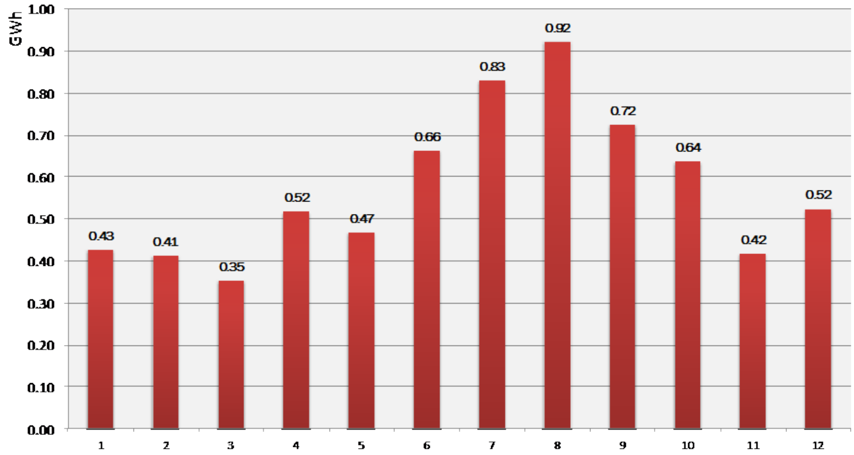


Figure 10.21. Monthly energy consumption of Alcantarilha WTP in 2011.

10.4.2 Potential for energy production in Alcantarilha WTP

The potential of micro hydro-generation solutions depends mainly on the total head available, measured as the vertical height from the turbine up to the point where the water enters the intake pipe or penstock, and also from the flow rate available. In Alcantarilha WTP the head availability at the intake pipe varies during the year, with an average value of 22 m, as can be observed in Figure 10.22.

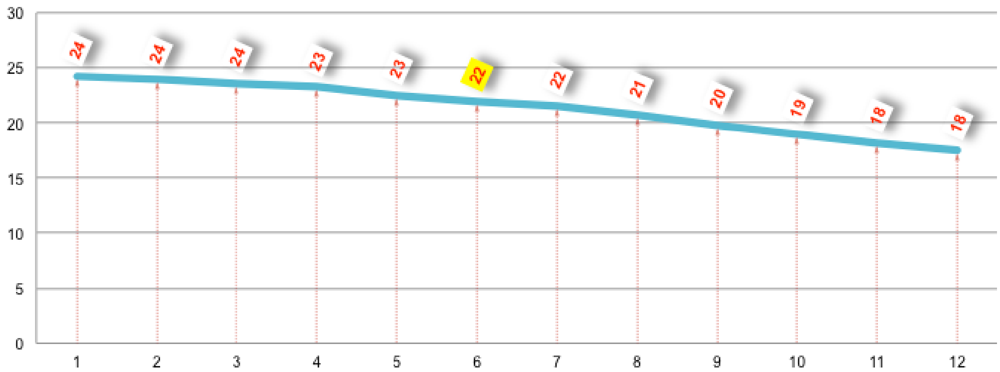


Figure 10.22. Average monthly hydraulic head (m) availability at the intake pipe of Alcantarilha WTP.

The flow availability has a wide range of variation along the year, due to the seasonal effects already mentioned. Seasonal effects increase the negative impact which uncertain future events and thus must be taken into account in the cost-benefit analysis for choosing and installing a micro hydro-generation solution. The lowest flow availability in Alcantarilha WTP occurs during winter, and the peak is reach usually during July and August, as can be observed in Figure 10.23.

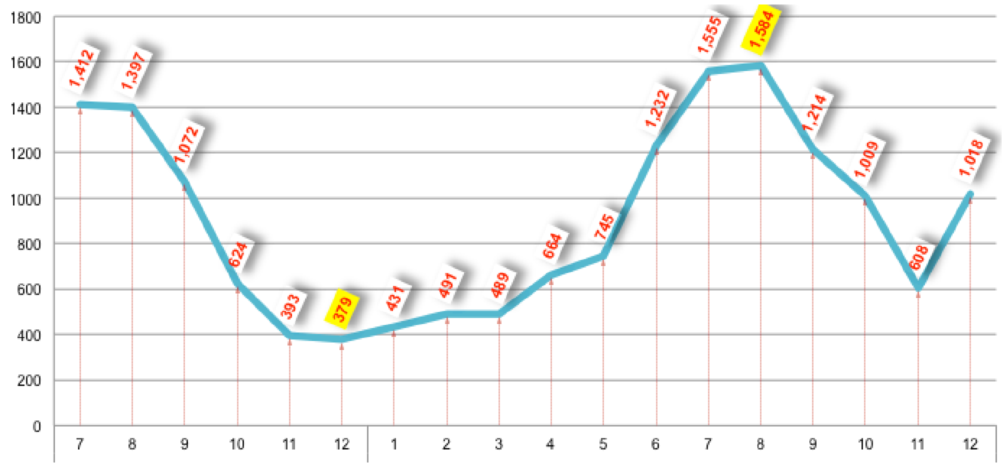


Figure 10.23. Average monthly water flow (l/s) availability at the intake pipe of Alcantarilha WTP.

After the analysis of the standard deviation of the available flow-rate, due to the seasonal effects, a cross-flow turbine was chosen to be implemented. Although cross-flow turbine has peak efficiencies lower than of Kaplan, Francis or Pelton turbines, the main advantage of this technology is that it is characterized by a flat efficiency curve under varying load. With a split runner and a turbine chamber, it maintains its efficiency while the flow and load vary from 1/6 to the maximum, which will provide a better adjustment to the varying flows of the system.

Figure 10.24 shows the efficiency curve of an Ossberger cross-flow turbine and the equivalent Francis turbine.

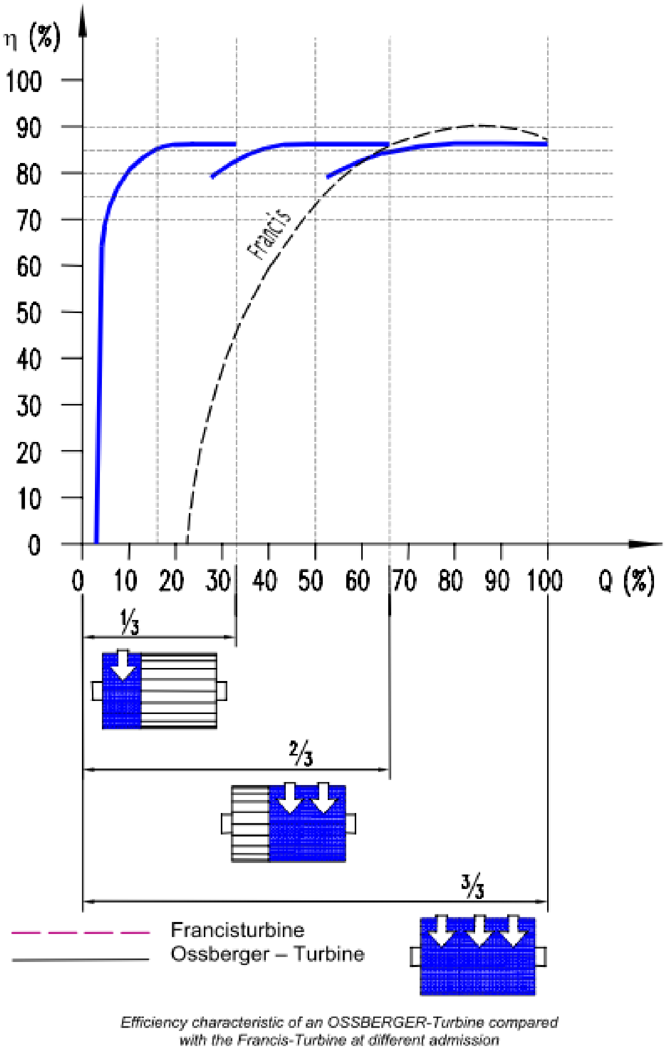


Figure 10.24. Efficiency characteristic of an Ossberger turbine compared with the Francis turbine at different admission

Other advantages are:

- No lubricants are admitted to the water
- Maintenance is limited to annual change of grease
- Smooth, vibration-free operation without cavitation

Base on the head availability, average flow availability and the technical characteristics of the turbine chosen, the average monthly electrical power output availability was calculated, based on 2011 data. Figure 10.25 presents the corresponding monthly power output.

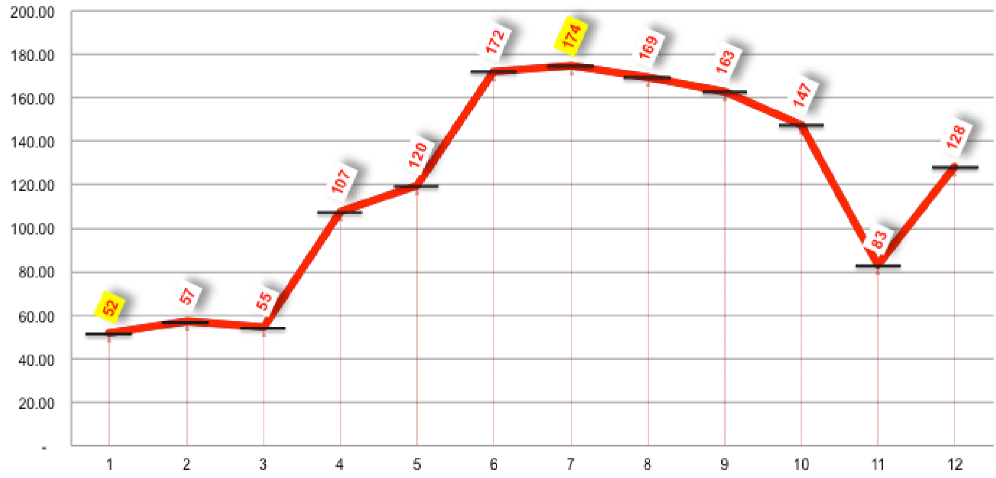


Figure 10.25. Average monthly electrical power output availability (kW).

10.4.3 Cash flows calculation

Alcantarilha's Mini-hydro has a permit allowing the respective grid-connection, in 15kV, according to the national law Decreto-Lei n.º 34/2011, to feed the renewable electricity into the grid. Due to the feed-in-tariffs, the government takes over an important part of the risk and the energy provider will receive a fixed price (guaranteed by the government) for the power generated during a fixed period.

The risk associated with the investment was analyzed through a Net Present Value (NPV) calculation of the expected cash flows. A reference scenario was admitted for granted during the fixed period of the feed-in-tariffs (15 years), considering a discount rate of 4% and an initial investment of 550 000 €. Maintenance cost was assumed as 30 000/year and the tariff was set to 0.125 €/kWh.

The NPV obtained is presented in Figure 10.26 and revealed a payback time of 8 years, with a total NPV of 336 k€ after 15 years.

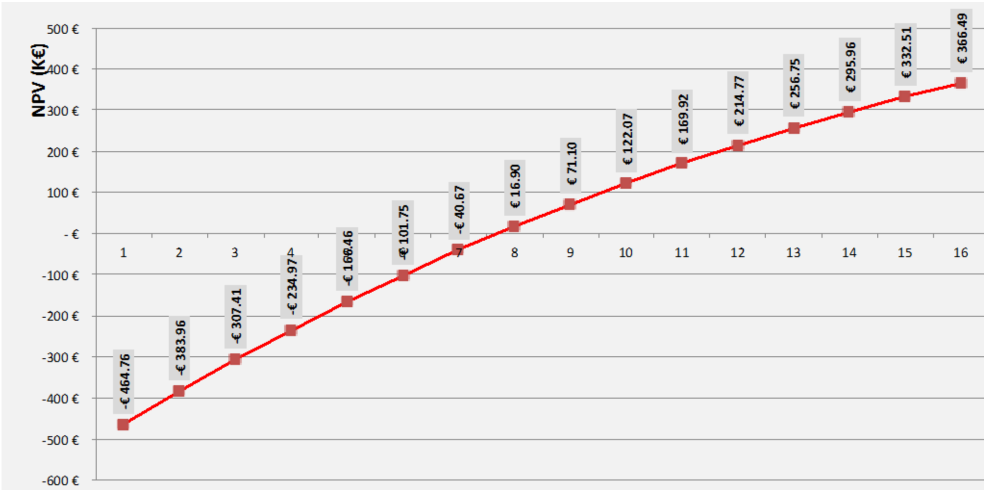


Figure 10.26. Net Present Value of investing in a cross-flow turbine.

The power generated by the cross-flow turbine would enable an injection of aproximatelly 1 000 MWh/year into the public grid, avoiding the emission of 631 $\text{ton } CO_{2eq}$ and the consumption of 89.3 toe.

10.5 Summary and conclusions

Águas do Algarve S.A. has invested in micro-hydro production. Among the electricity production facilities, the Beliche power plant is currently operating, using two pumps-as-turbine to profit from the head in Beliche dam and the flow used in the Beliche water treatment plant.

Its current operational scheme can be improved if the energy generation happens throughout the year, instead of only during the high season. Another possible improvement is the regulation of the turbinated flow.

There is also room for a third future turbine to be installed next to the existing ones.

O&M of Beliche and Tavira WTP have been neglected in the analysis. If these costs were taken into account, the operation of the hydropower plant would not be viable, as O&M costs of Beliche WTP are almost five times the ones of Tavira WTP. In this context, dimensions of analysis such as the risk, the performance and the use of renewable energy sources should be considered in the analysis.

For the Alcantarilha WTP the NPV potential of the investment in micro hydro-generation is much more attractive with a payback time of 8 years and a total NPV of 336 k€ after 15 years.

10.6 References

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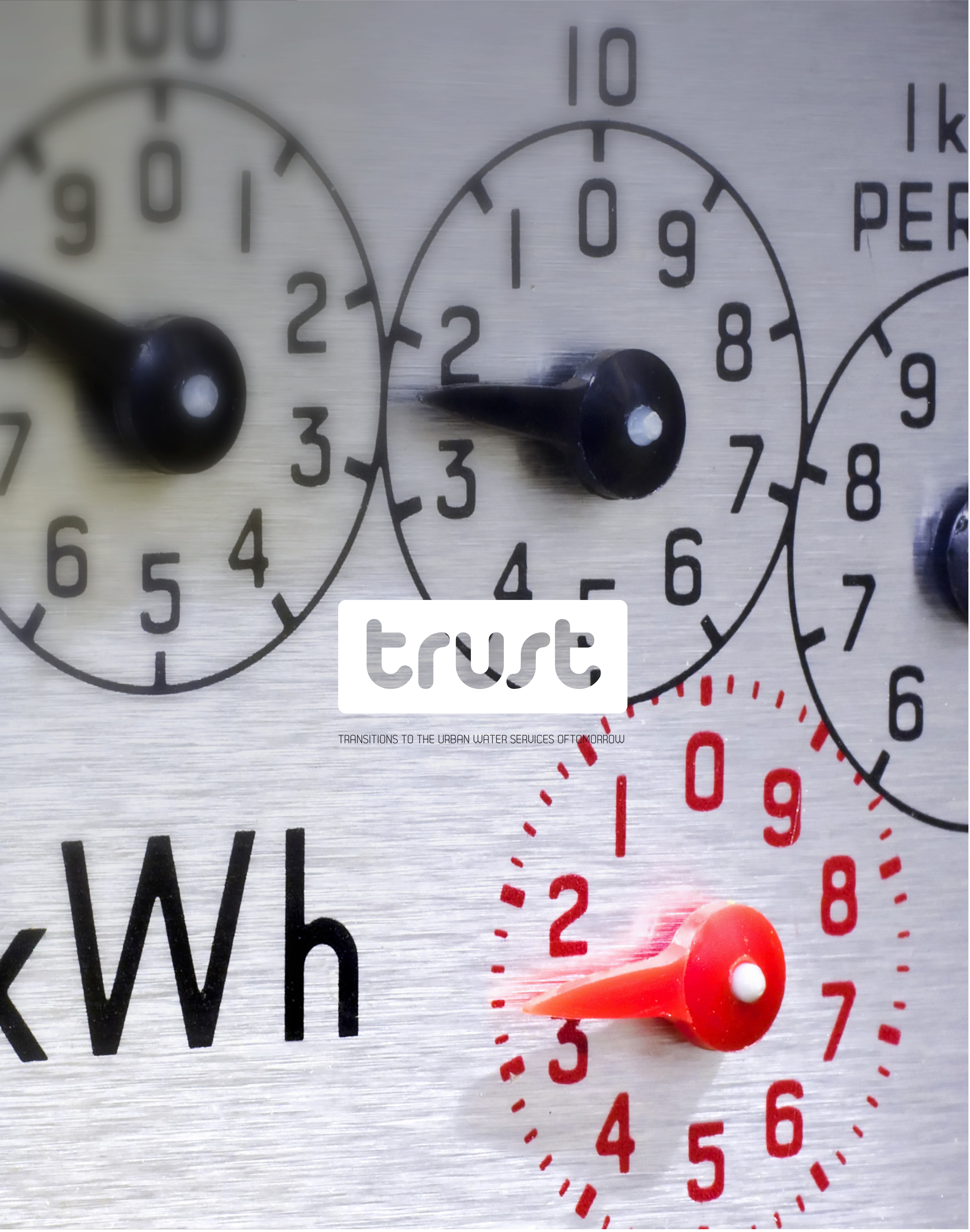

Intervention concepts for energy saving, recovery and generation from the urban water system **D 45.1**

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265122.