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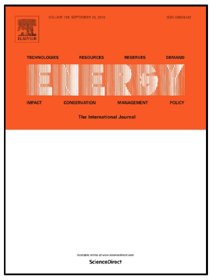

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Energy Recovery from the Water Cycle: Thermal Energy from Drinking Water

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Abstract

Greenhouse gas (GHG) emissions contribute to climate change. The public water utility of Amsterdam wants to operate climate neutrally in 2020 to reduce its GHG emissions. Energy recovery from the water cycle has a large potential to contribute to this goal: the recovered energy is an alternative for fossil fuel and thus contributes to the reduction of GHG emissions. One of the options concerns thermal energy recovery from drinking water. In Amsterdam, drinking water is produced from surface water, resulting in high drinking water temperatures in summer and low drinking water temperatures in winter. This makes it possible to apply both cold recovery and heat recovery from drinking water. For a specific case, the effects of cold recovery from drinking water were analyzed on three decisive criteria: the effect on the GHG emissions, the financial implications, and the effect on the microbiological drinking water quality. It is shown that cold recovery from drinking water results in a 90% reduction of GHG emissions, and that it has a positive financial business case: Total Cost of Ownership reduced with 17%. The microbial drinking water quality is not affected, but biofilm formation in the drinking water pipes increased after cold recovery.

Keywords

Cold recovery; Greenhouse gas emissions; Drinking water; Microbiological water quality; Thermal energy

1. Introduction

It is generally accepted that emission of greenhouse gases (GHG) contributes to climate change. Already in 2007 the International Panel on Climate Change (IPCC) recommended to strive for an ambitious reduction of carbon dioxide-equivalent (CO_2) emission levels in order to stabilize global warming [1]. In 2013 the IPCC stressed again that continued emissions of GHG will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of GHG emissions [2]. Based on the conclusions of the IPCC, targets and ambitions have been formulated at many levels, ranging from a worldwide level (United Nations) to a city level and public utility level, e.g. water utility Waternet in Amsterdam. Table 1 summarizes the targets set at these different levels.

Table 1. Climate change mitigation targets at different levels

Level	Organization	Targets	References
World-wide level	United Nations	• keep global temperature rise this century well below 2 ^oC above pre-industrial levels • pursue efforts to limit temperature increase further to 1.5 ^oC	3, 4
European level	European Union	• 40% cut in GHG emissions	5

		compared to 1990 levels • at least 27% share of renewable energy consumption • at least 27% energy savings compared with the business as usual scenario	
National level (Netherlands)	Ministry of Economic Affairs and Climate Policy	• 95% reduction GHG in 2050 • abandoning the use of fossil fuel in 2050	6
Municipal level (Amsterdam)	City of Amsterdam	• 40% reduction in GHG emissions in 2025 compared to 1990 • 75% reduction in GHG emissions in 2040 compared to 1990	7, 8
Utility level	Waternet	• Climate neutral operation in 2020	9

Waternet is the public water utility of Amsterdam and surroundings and responsible for the water management. Waternet is owned by the City of Amsterdam and the Regional Water Authority Amstel, Gooi and Vecht. The activities of Waternet concern drinking water supply, sewerage, wastewater treatment, surface water management, groundwater management, control of the canals of Amsterdam and flood protection. The broad scope of these activities implies that Waternet manages the whole water cycle. Also Waternet has set goals with respect to reduction of GHG emissions: in 2020 Waternet has the ambition to operate climate neutrally [9]. A climate neutral operation is defined as an operation without a net GHG emission. From 1990 to 2016 the GHG emission of Waternet decreased from 114,196 ton CO_2-eq to 37,203 ton CO_2-eq, as shown in Figure 1.

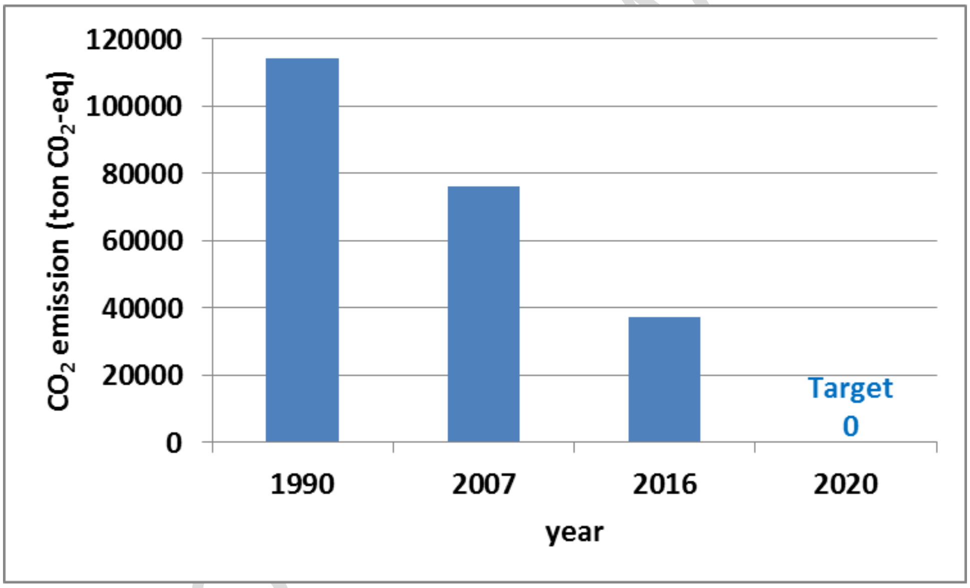

Figure 1. Greenhouse gas emissions of Waternet

This reduction has been realized by a combination of measures, such as energy savings, process optimizations (focusing on the use of raw materials and chemicals with less impact on GHG emissions), and by the use of renewable energy [10, 11]. An important measure concerned the move to 100% renewable electricity, resulting in a decrease of GHG emissions from 42 kton CO_2-eq/a to 2.4 kton CO_2-eq/a. Also the start of a new wastewater treatment plant adjacent to the Amsterdam waste-to-energy plant contributed to the reduction. Biogas and sludge from the wastewater treatment plant are burned in the Amsterdam waste-to-energy plant. The waste heat from the biogas and sludge combustion is efficiently used to heat buildings at the wastewater treatment plant and to speed up the sludge digestion process, in which originally natural gas was used. The related GHG emissions (gas, heating) reduced from 5.3 kton CO_2-eq/a to 1.85 kton CO_2-eq/a. Also energy recovery from surface water contributed substantially. In a specific project cold is recovered from the lake “Ouderkerkerplas” and used for cooling of office buildings, resulting in a reduction of GHG emission of almost 20 kton CO_2-eq/a as compared with the use of traditional cooling machines in the office buildings.

Figure 1 shows that although an important reduction has been realized, additional measures have to be taken to realize the target in 2020. The policy of Waternet is to select measures which can be incorporated in the operations of Waternet, while in addition the measures have to be cost neutral. An inventory has been made recently [12]. As a water cycle utility in an urban environment, it is obvious to examine in detail energy in the urban water cycle. On the one hand the water cycle uses energy, as described by Elías-Maxil et al [13]: energy is used for drinking water production, during water consumption, and after use for transport and treatment of wastewater. On the other hand, the water cycle offers opportunities to recover energy from the water cycle [14, 15] and the recovered energy may be used as an alternative for fossil fuel. In this way energy recovery from the water cycle may be seen as a compensation measure for the inevitable GHG emissions of Waternet, caused by the use of chemicals and raw materials in the water treatment processes.

Figure 2 shows the possibilities the water cycle offers: chemical energy from wastewater, and thermal energy from wastewater, surface water, groundwater and drinking water.

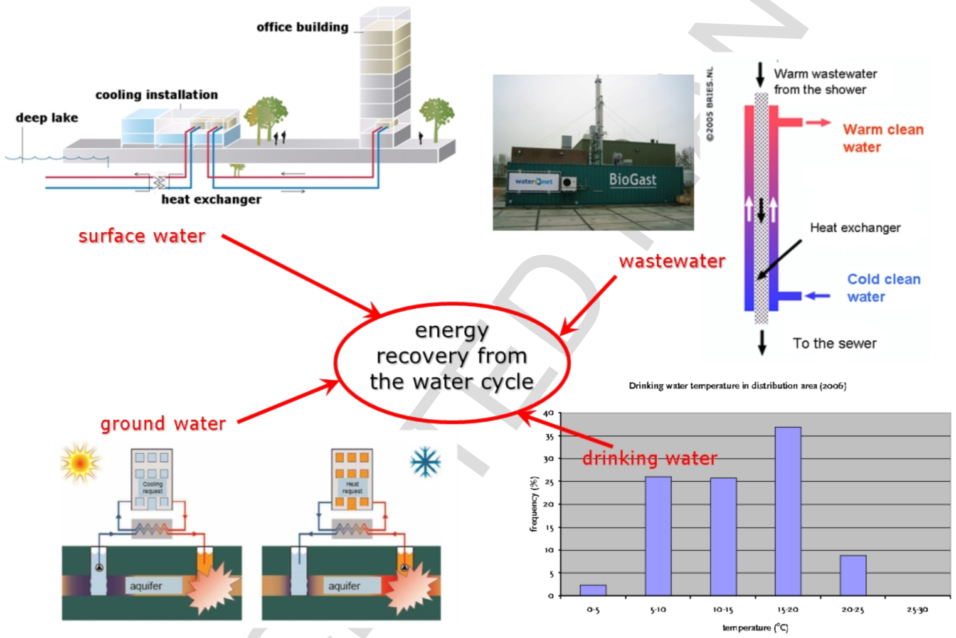

Figure 2. Possibilities of energy recovery from the water cycle

A detailed study into energy recovery from the water cycle in Amsterdam was made in 2013 [16]. Figure 3 shows the results. The research showed a large potential: by recovering energy from the water cycle, the use of fossil fuel can be avoided and emission of GHG can be decreased with 82,000 ton CO_2-eq/a in a maximum scenario, and 27,300 ton CO_2-eq/a in a minimum scenario. In the minimum scenario it was assumed that only projects with a positive business case will be realized, and that not all reductions in GHG can be contributed to Waternet, as projects will be realized in co-operation with partners.

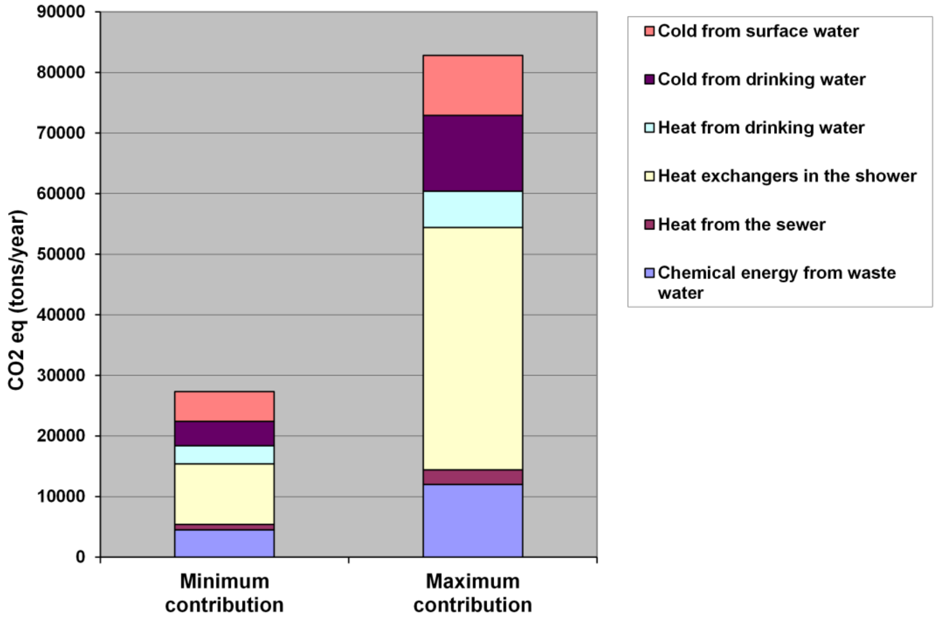

Figure 3. Energy recovery from the water cycle in Amsterdam, expressed as avoided greenhouse gas emissions (reprinted from Journal of Water and Climate Change, volume 5, Issue 1, pages 61-69, with permission from the copyright holders, IWA Publishing)

With respect to chemical energy from wastewater, Waternet already produces 11 million Nm^3/a biogas via sludge digestion, but the ambition is to move towards products higher in the biomass value pyramid, such as materials & chemicals, food products, and health & lifestyle products, which may conflict with biogas production [17]. Heat recovery from wastewater by the use of heat exchangers in the sewer has been studied in detail [18, 19] but based on possible operational problems, such as fouling and clogging of the heat exchangers [20], this technology is not implemented in Amsterdam. A pilot study to heat recovery from the shower showed a large potential for this technology [21] with energy savings up to 64% and a potential GHG emission reduction of 54 kton CO_2-eq/a, but Waternet has no influence on the implementation of this technology at the customer's premises. Thermal energy recovery from surface water can be applied for heat recovery by using shallow surface water as sun collector, and for cold recovery by using surface water, especially deep lakes, as "cooling machine" [22]. The latter is applied by Waternet in the lake "Ouderkerkerplas", where cold from the lake is delivered to a nearby office building resulting in a reduction of GHG emissions of 19.9 kton CO_2-eq/a. Simultaneously the water quality and the ecological quality of the lake are improved by removing phosphate from the water during abstraction [23]. Groundwater is used in aquifer thermal energy storage systems to match the thermal energy requirements fluctuations over the year and is applied at large scale nowadays [24], also in Amsterdam [23].

Waternet has no practical experience with thermal energy recovery from drinking water. The technology is based on the use of heat exchangers in drinking water transport pipes to recover thermal energy from the water. The potential is high (Figure 3). The fact that Waternet produces drinking water from surface water, combined with the large volume flows in the drinking water transport and distribution system, contribute to this potential. Based on the heat capacity of water, 4.2 MJ/(m^3.K), both temperature gradient and volume flow are important. The temperature varies between 1^{o}C in winter and 25 ^{o}C in summer [15], while volume flows up to 5,900 m^3/h transport the water from the production plants to the city of Amsterdam. The low and high temperatures make it possible to apply both cold recovery and heat recovery from the drinking water. In a recent report the possibilities were stressed of sustainable cooling of buildings in the city of Amsterdam [25]. The potential of cooling directly with drinking water was calculated to be 43 TJ/a, but this can only be offered in winter, when the cold demand is limited. The indirect cooling by using aquifer thermal energy storage, to store cold in winter and use it in summer, increases the potential up to 2,800 TJ/a. At the same time the total demand for space cooling of non-residential buildings in Amsterdam (hospitals and health care facilities, offices and company buildings, societal and leisure facilities) was estimated to be 2,161 TJ/a.

Thermal energy recovery affects the temperature of the drinking water. In the case of heat recovery, the temperature of the drinking water after having passed the heat exchanger will be lower, while in the case of cold recovery the temperature of the drinking water will be higher. While a lower drinking water temperature in the summer may have a positive effect on comfort aspects for the customer, a higher temperature may have a negative effect on the microbiological quality of the water. Microbiological growth and activity in drinking water transport and distribution systems depend on environmental conditions [26], and higher temperatures enhance biological activity and increase cell numbers [27, 28]. Drinking water transport and distribution systems are designed to avoid undesirable microbial proliferation during water distribution to supply microbial safe water at customers' taps. An important aspect is that in the Netherlands the drinking water is distributed without a persistent disinfectant [29, 30] which requires special attention to microbiological processes in the transport and distribution systems.

Throughout the world cold recovery from drinking water has not yet been applied in practice. The concept of thermal energy recovery from drinking water has recently been described. Guo and Hendel [31] explored potential techniques for emergency cold recovery from drinking or non-potable water networks in response to heat-waves. Paris was taken as an example. They presented three emergency cold recovery techniques: subway station cooling, ice production for individual cooling, and "heat-wave shelter" cooling in association with pavement-watering. Application in practice did not yet take place. De Pasquale et al [32] analyzed the integration of a district heating heat pump with the drinking water network – playing the role of low temperature heat source – as an alternative to conventional fossil fuel heating in the city of Milan. To evaluate the system performance a tailored-made model was developed. The system has not yet been applied in practice. In a recent review of district heating and cooling Werner [33] points at renewable heat and cold supply methods, but drinking water was not mentioned as a potential source. Bloemendal et al. [34] described the possibility of thermal energy recovery from drinking water pipes and sewer pipes and concluded that these were determined by local circumstances. In a follow-up study Hofman and Van der Wielen [35] focused on the risks of thermal energy recovery from drinking water pipes and sewer pipes. The risks concerned financial risks and also water quality risks for thermal energy recovery from drinking water. In practice there is only very limited experience with these systems, while the energetic yield and economic benefits are still unclear [36]. Only for a specific case a cost benefit analysis has been made for an entire city (Almere, the Netherlands), but this concerned heat recovery from drinking water originating from groundwater, in which the temperature of the treated water was only lowered 1.16 ^{o}C. [37].

The objective of this study was to analyze the potential of cold recovery from drinking water originating from surface water on three decisive criteria: 1) the effect on the GHG emissions of Waternet, as it has to contribute to the target of Waternet to operate climate neutrally in 2020; 2) the financial effects, as an important condition is that measures to operate climate neutrally have to be cost neutral and 3) the effect on microbiological drinking water quality, as the technology may not result in a deterioration of the drinking water quality.

This paper is structured as follows: section 2 presents the materials and methods used to analyze the GHG reduction, to calculate financial effects and to measure the microbiological effects of cold recovery from drinking water, and section 3 sets out the case study "Sanquin-Waternet" to quantify the impact of cold recovery from drinking water on GHG emissions and costs. Section 4 covers results and discussion, followed by the conclusions in section 5.

2. Materials and Methods

2.1 Greenhouse gas emissions and cooling performance

GHG emissions were calculated based on the international Greenhouse Gas Protocol [38]. To determine the effect of GHG emissions on the climate footprint, the Intergovernmental Panel on Climate Change Global Warming Potential (IPCC GWP) 100a method [39] was used. Within this method, only the environmental problem of climate change is evaluated and the results are expressed in CO_2 equivalents. In the Greenhouse Gas Protocol, emissions are divided in three scopes:

- Scope 1: direct GHG emissions. Direct GHG emissions occur from sources that are owned or controlled by the company. This covers the emission of CO_2, due to the use of fossil fuels, and the emissions of nitrous oxide (N_2O) and methane (CH_4) as process emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc., and emissions from chemical production in owned or controlled process equipment.
- Scope 2: electricity indirect GHG emissions. Scope 2 accounts for GHG emissions from the generation of purchased electricity consumed by the company. Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where the electricity is generated.
- Scope 3: other indirect GHG emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Indirect emissions result from, for example, extraction and purchased materials (chemicals, raw materials) and fuels, transport-related activities, waste disposal and use of sold products and services.

SEER values (Seasonal Energy Efficiency Ratio) were used to calculate the cooling performance:

$$SEER = \frac{\text{output cooling energy in BTU over a season}}{\text{input electrical energy in Wh during the same season}} \qquad \text{(equation 1)}$$

in which BTU is British Thermal Unit (1 BTU = 0.293 Wh).

2.2 Cost evaluation

Costs of cold recovery from drinking water were based on the Total Cost of Ownership (TCO) concept, that calculates capital costs and operational costs for a chosen evaluation period. A general equation for TCO is:

$$TCO = P + \text{Net Present Value of } (O+M+E-R) \qquad \text{(equation 2)}$$

where:

P = Purchase costs
O = Operating costs
M = Maintenance costs
E = Environmental costs
R = Residual value

In equation 1, more specific components can be introduced, such as Training costs, Warehousing costs, Distribution costs, etc.

Since the installation for cold recovery is composed of a large number of components, each with its own life time, using Purchase costs and a short evaluation period could lead to an undesired emphasis on the Residual value. Instead, Capital costs are introduced by adding up the depreciation costs and the interest costs of each component, based on its technical life time, in combination with a long evaluation period. The equation for TCO then becomes:

$$TCO = \text{Present Value of } (C+O+M+E-R) \qquad \text{(equation 3)}$$

where:

C = Capital costs of the initial investment and re-investments
O = Operating costs
M = Maintenance costs
E = Environmental costs
R = Residual value

For this project, an evaluation period of 30 years was chosen, to include at least one replacement cycle of major components, such as pumps. The capital costs are based on the initial investment sum and re-investment sums during the evaluation period, corrected for annual inflation. The operational costs include costs for energy, resources and maintenance. Environmental costs include costs for CO_2 emissions. The annual capital expenditure (capex) and operational expenditure (opex) result in the total costs for each year. Over the total evaluation period the TCO is calculated by adding up the net present values of all the annual total costs, using an interest rate of 2%.

2.3 Microbiological effects

Effects on microbiological drinking water quality and biofilm formation were studied in three laboratory scale drinking water distribution systems (DWDS). Figure 4 shows the systems: system 1 is the study system with an operational heat exchanger for cold recovery, system 2 is the control system with an installed but not in operation heat exchanger to study the effect of additional surface area in the distribution system, while system 3 is the reference system without heat exchanger. The drinking water used as feed water for all three systems was coming from Kralingen treatment plant of Evides drinking water company (Rotterdam, The Netherlands).

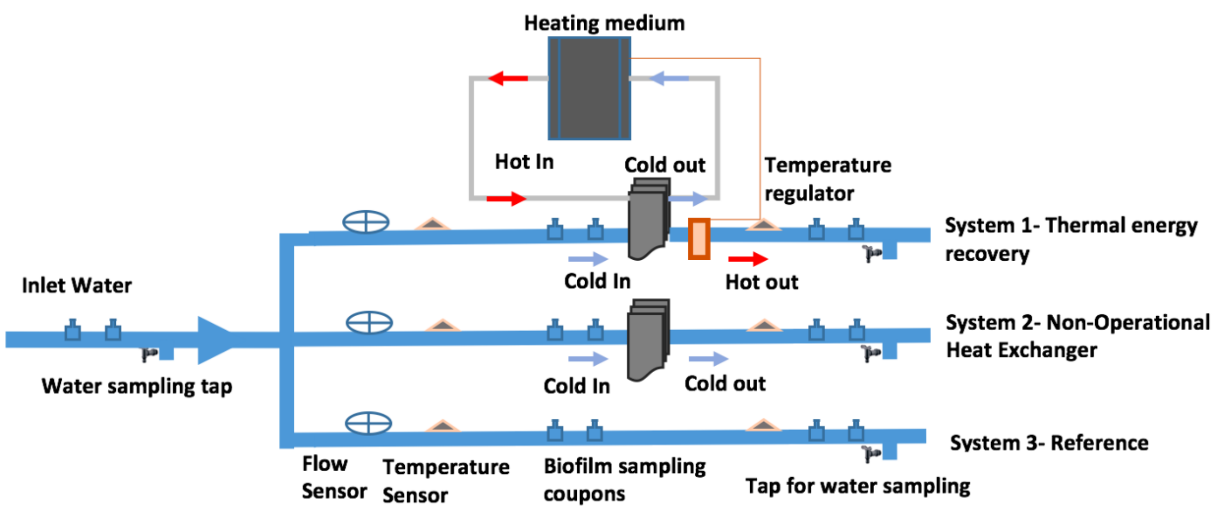

Figure 4. Laboratory scale drinking water distribution systems

The heat exchangers in systems 1 and 2 were 6 plates stainless steel heat exchangers, with a total heat transfer area of 0.096 m^2, with 3 channels at the drinking water side and 2 channels at the heating medium side (Tranter International AB). In system 1 the thermal energy exchange was mimicked by use of a water bath and heating medium to heat the drinking water in the heat exchanger. The heating medium inlet temperature was 45 ^oC. Table 2 summarizes the operational conditions of the three laboratory scale systems. The systems were operated for a period of eight months (May to December 2016). As these preliminary laboratory experiments were carried out partly in the summer, the inlet drinking water temperature was relatively high (18-19 ^oC) compared to the inlet drinking water temperature at which the full-scale installation in the "Sanquin-Waternet" case is operated (temperatures below 15 ^oC), as will be described in section 3.The temperature in the outlet of system 1 with an operational heat exchanger was set at 24 ^oC, as in the Netherlands the drinking water temperature is limited to a maximum of 25 ^oC according to the Dutch Drinking Water Directive [40]. The flow velocity in the DWDSs was based on the characteristics of self-cleaning networks [41]. The systems were equipped with flow sensors, temperature sensors, biofilm sampling coupons for biofilm analyses and water sampling taps for bulk water analyses.

Table 2. Operational conditions of the laboratory scale drinking water distribution systems (DWDSs)

	Laboratory scale DWDS		
	1	2	3
Flow rate (l/m)	4.5	4.5	4.5
Flow velocity (m/s)	0.15	0.15	0.15
Inlet temperature (^oC)	19	18	19
Outlet temperature (^oC)	24	18	19
Pipe material	PVC	PVC	PVC
Pipe diameter (mm)	25	25	25
Length of the system (m)	10	10	10

2.4 Water sampling and biofilm sampling

Water was sampled from four sampling locations, as indicated in Figure 4: the incoming water before thermal energy recovery (BTER), the water after thermal energy recovery in system 1 (ATER), the water after passing a non-operational heat exchanger in system 2 (AHE), and the water after passing the reference system without a heat exchanger in system 3 (REF). Every week water samples were collected in HD-PE plastic bottles to perform the analysis within 24 hours of sampling.

The biofilm samples were collected once, at the end of the experiment (after 38 weeks) from the same four sampling locations as for taking water samples. Specially designed PVC coupons were used for biofilm sampling. The 25-cm long pipe sections connected with valves on both sides were taken out of the systems and filled with autoclaved tap water and valves were closed. Subsequently the pipe sections were ultra-sonicated at low sonication (42 kHz) in a water bath for 2 minutes. After sonication suspension was obtained and pipe sections were filled again with new autoclaved tap water to repeat the sonication procedure [42, 43]. This procedure was repeated three times and the obtained solution was used for different analysis.

2.5 Microbiological water quality and biofilm analysis

Microbiological water quality and biofilm analysis concerned Total Cell Concentrations (TCC) and Adenosine Tri Phosphate (ATP) concentrations to quantify biomass, while *Aeromonas* spp. and *Legionella* spp. were measured as opportunistic pathogenic micro-organisms.

TCC was measured by direct cell count using Flow Cytometry Method, using the same protocol that has been previously developed and tested for drinking water samples [44, 45]. ATP as measure for active biomass was determined using a reagent kit for bacterial ATP and a luminometer as has been described in the protocol previously developed [42]. *Aeromonas* was analysed using NEN standard 6263 [46]. The colony forming units of *Legionella* were determined using buffered charcoal yeast extract agar according to NEN standard 6265 [47].

3. Case study

For the GHG analysis and the cost analysis a specific case was selected: the “Sanquin-Waternet” case. Sanquin produces plasma products from blood and needs cooling capacity for the pharmaceutical production processes and for the storage of products. As shown in Figure 5, just along Sanquin a 700 mm drinking water main of Waternet passes. This main is used as a source for cooling capacity. A branch has been made in this main (diameter 200 mm), transferring cold water to a heat exchanger. The heat exchanger (Sondex) has 542 plates and a total heat transfer area of 715.5 m^2. The flow at the cold side of the heat exchanger (water) is 500 m^3/h, the flow at the hot side of the heat exchanger (65% water – 35% glycol) is 552 m^3/h. Through the use of a double-walled heat exchanger it is ensured that the drinking water is safely separated from Sanquin’s cooling system. A separate cold transport line is used to supply cold to the processes at the Sanquin site. The heat released from these processes is transferred back to the drinking water via the heat exchanger and a second branch (200 mm) in the 700 mm drinking water main.

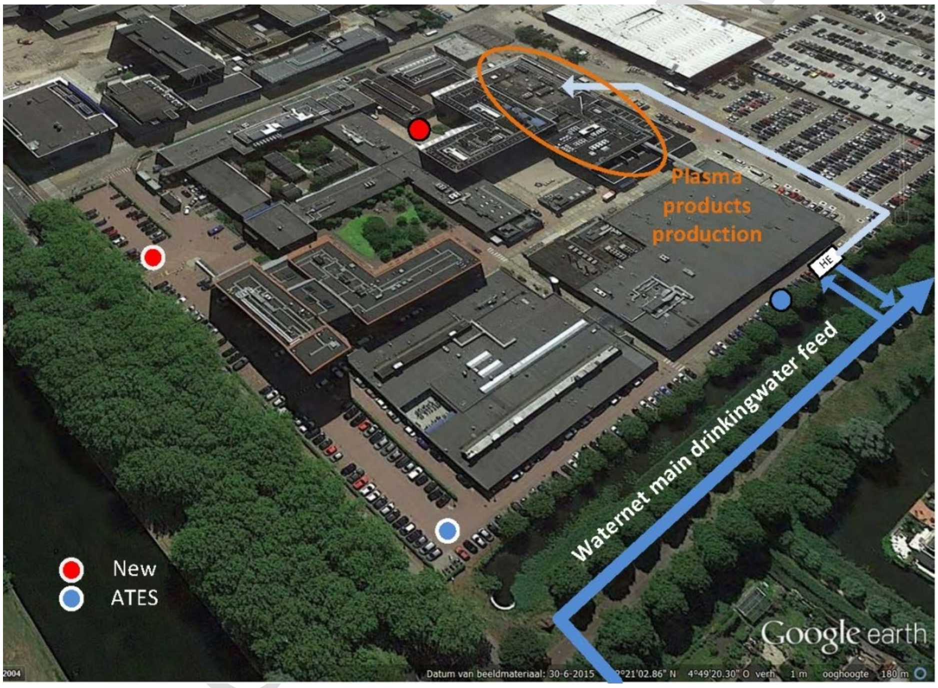

Figure 5. Delivery of cooling capacity through a Waternet main, via a heat exchanger (HE) to Sanquin. The red and blue dots are the hot and cold wells of two aquifer thermal energy storage systems

As the microbiological effect of cold recovery on the drinking water quality is not yet known, the Human Environment and Transport Inspectorate of the Ministry of Infrastructure and Water Management, in charge of the surveillance of the drinking water quality, has limited the drinking water temperature after the heat exchanger to 15 ^oC. In practice this means that the system is in operation as long as the incoming drinking water temperature of the heat exchanger is below 14 ^oC. After the heat exchanger a temperature of 15 ^oC is allowed. When the drinking water temperature before the heat exchanger exceeds 14 °C, the system is put off. So, the heat exchanger is only operational from November till April, when the incoming drinking water temperature is below 14 °C and warming up to 15 °C is possible. However, by combining the system with an aquifer thermal energy system (ATES) shown as red and blue dots in Figure 5, cooling capacity from drinking water can be delivered the whole year. Figure 6 shows the principle. During winter cooling capacity can be delivered directly. In addition, groundwater is pumped from a well beneath the ground and cooled through the heat exchanger. This cooled groundwater is then stored in the cold well. During the summer months, the drinking water is not cold enough and the exchange process is stopped. However, the cooled groundwater that has been stored underground in the ATES can be used for cooling Iin summer.

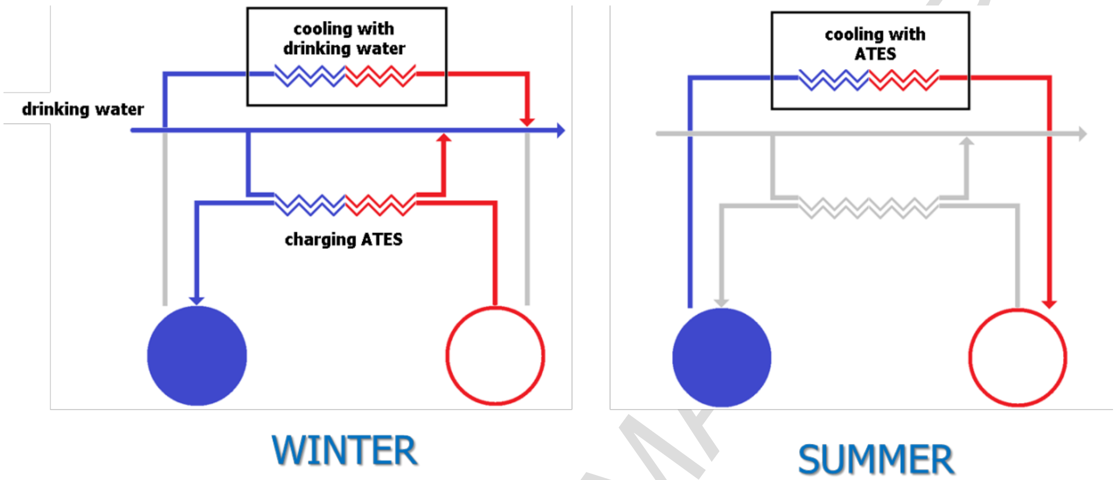

Figure 6. Process set-up of cooling with drinking water under winter and summer conditions

4. Results and discussion

4.1 Reduction of GHG emissions and increase in cooling performance

The results with respect to reduction of GHG emissions and the increase of the cooling performance are shown in Table 3. This table compares two situations: the use of conventional cooling machines for cooling capacity, and the use of drinking water for cooling capacity. As the new installation set-up is not yet in use a whole year, some estimates had to be made, but seasonal variations were taken into account and thus SEER values can be calculated.

The yearly needed cooling at Sanquin is 15,523 MWh which equals 53,0x10^9 BTU. Based on a drinking water flow through the heat exchanger of 500 m^3/hr during winter, and an average temperature difference of 7.5 °C, 17,250 MWh of cooling can be produced annually, so the demand can be fulfilled.

The existing (conventional) cooling system of Sanquin consists of different types of free cooling and compression cooling units, operating at different temperature ranges. The year-round COP (coefficient of performance) of the existing system is 9. The yearly electricity consumption of the conventional system is then 1,725 MWh, so SEER equals 31. The year round COP of the drinking water – ATES system is estimated at 90. With the same yearly needed cooling the yearly electricity consumption of the drinking water – ATES system is 172.5 MWh, so SEER equals 307.

The reduction of electricity consumption from 1,725 MWh/a to 172.5 MWh/a leads to a reduction of GHG emissions of 869 ton CO_2-eq/a, using the CO_2 emission coefficient for Dutch electricity, based on the actual energy mix (0.56 kg CO_2-eq/kWh).

Table 3. Electricity use, GHG emissions and cooling performance of two systems for cooling in the "Sanquin-Waternet" case

	Electricity use (MWh/a)	GHG emission (ton CO_2-eq/a)	Cooling performance (SEER value)
Traditional cooling machines	1,725	966	31
Cooling with drinking water	172.5	97	307

The total potential of thermal energy recovery from drinking water may be even higher than just the Sanquin-Waternet case. First condition is that it should be allowed to heat up the drinking water after the heat exchange above 15 °C. Until now the limit has been set at 15 °C for safety reasons. Research in the laboratory scale experiments have to reveal whether higher temperatures (without negative effects on microbiological water quality), and thus a higher GHG emission reduction, are feasible. Secondly, in Amsterdam additional locations have to be found where thermal energy supply and demand matches and additional project can be realized to increase the contribution of thermal energy recovery in the target of 37,203 ton CO_2-eq. Although the total supply potential of cooling with drinking water and the total demand for cooling of non-residential buildings in Amsterdam seem to be balanced (2,800 TJ/a and 2,161 TJ/a respectively [24]), every project has to be evaluated individually. Investments may be too high, or other alternatives like cooling with surface water may be more attractive.

4.2 Costs

The results with respect to the costs are summarized in Table 4.

Table 4. Total Cost of Ownership (TCO) of two systems for cooling in the "Sanquin-Waternet" case

	Traditional cooling machines	Cooling with drinking water
Preparation costs (€)	80,000	222,191
Capital costs (€)	3,670,717	6,223,697
Maintenance costs (€)	3,330,025	2,575,355
Operating costs (€)	4,137,944	196,635
Total costs (€)	11,218,686	9,217,875
TCO (million €)	8.2	6.8

Based on the TCO, the system using cooling with drinking water has a 17% lower TCO as compared with the system using traditional cooling machines. Although the investments for cooling with drinking water result in higher capital costs, the operating costs are much lower due the large decrease in electricity use. In addition, specific for the "Sanquin-Waternet" case, by using cooling with drinking water it is not necessary to extend the existing electricity infrastructure, and noise reducing measures are not required. Also, traditional cooling machines require a footprint which is not available.

Despite the fact that the economic evaluation of these kind of projects depends strongly on local situations, it is interesting to make a comparison between different projects applying thermal energy recovery from drinking water. As already mentioned in the introduction, there is very limited experience with this technology. In a project in the city of Culemborg, The Netherlands, 192 houses and 8 business premises are heated with thermal energy recovered from a drinking water reservoir of a nearby pumping station. The TCO of a conventional system (using individual gas boilers) and a system using heat from drinking water were compared. The latter resulted in a 15% lower TCO [36].

4.3 Effect on microbiological drinking water quality and biofilm formation

Figure 7 shows the Total Cell Concentrations (TCC) and ATP concentrations in the bulk water phase in the laboratory scale DWDSs.

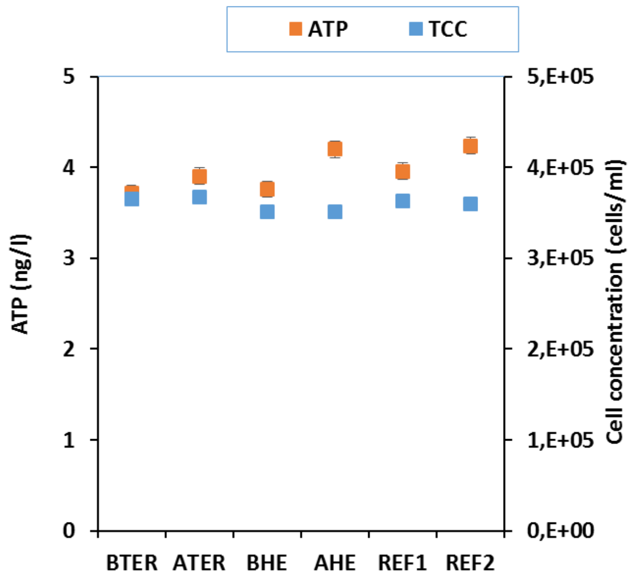

Figure 7. Microbiological water quality in DWDS 1 (BTER: before thermal energy recovery; ATER: after thermal energy recovery), DWDS 2 (BHE: before heat exchanger; AHE: after heat exchanger) and DWDS 3 (REF1: at start of DWDS; REF 2: at end DWDS) (n=29)

The results reveal similar microbiological water quality in both systems with a heat exchanger (operational heat exchanger – system 1, and non-operational heat exchanger – system 2), before and after the heat exchanger, and in the reference system (system 3). This stable microbiological quality in the bulk water phase is contradictory to previous researches which have reported significant changes in TCC because of seasonal temperature changes [48, 49, 50, 51, 52]. It may be due to the short distance and retention time of the water (about one minute), which is too short for significant changes to occur. Another factor is the drinking water treatment philosophy applied in the Netherlands: transport and distribution of drinking water without chlorine [29, 30] which is only possible at a very low nutrient level, preventing regrowth in water, also at elevated temperatures. Regarding the selected micro-organisms, *Legionella* spp. and *Aeromonas* spp., the water quality was also stable in the three DWDSs, as shown in Figures 8 and 9.

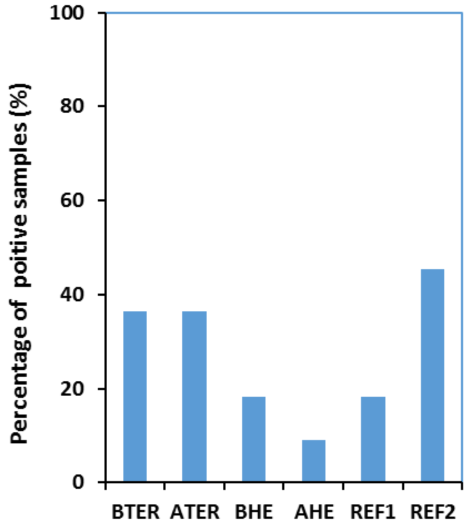

Figure 8. Positive *Legionella* spp. samples in bulk water in DWDS 1 (BTER: before thermal energy recovery; ATER: after thermal energy recovery), DWDS 2 (BHE: before heat exchanger; AHE: after heat exchanger) and DWDS 3 (REF1: at start of DWDS; REF 2: at end DWDS) (n=11)

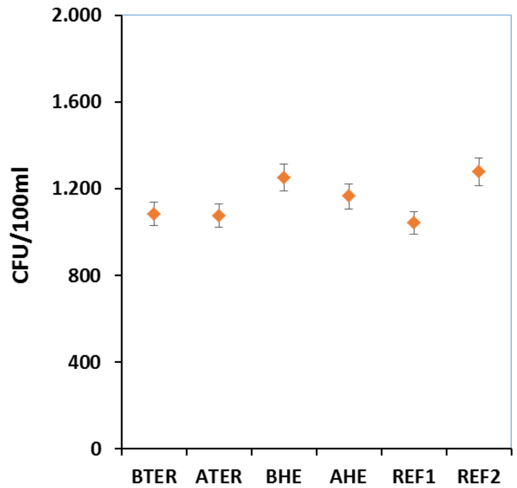

Figure 9. *Aeromonas* spp. in bulk water in DWDS 1 (BTER: before thermal energy recovery; ATER: after thermal energy recovery), DWDS 2 (BHE: before heat exchanger; AHE: after heat exchanger) and DWDS 3 (REF1: at start of DWDS; REF 2: at end DWDS) (n=8)

Figure 8 shows that *Legionella* was already present in the incoming water and does not increase after passing the heat exchanger, neither in the system with the operational heat exchanger (system 1), nor in the system with the non-operational heat exchanger (system 2). Figure 9 shows comparable numbers for *Aeromonas* spp. in all three systems, irrespective of higher temperature after cold recovery. The absence of enhanced proliferation of specific microbes including opportunistic pathogens may be due to the fact that the temperature remained below 25 ^{o}C [53].

In contrast, higher cell numbers and biological activity were detected in biofilm formed after cold recovery compared to the biofilm before cold recovery (2.5 times higher TCC and ATP, Figure 10). The observed higher biofilm formation at increased temperature is in consistence with previous researches, which found that temperature increase promoted biofilm formation rate on the pipe wall and bacterial growth kinetics were governed by temperature in the biofilm phase [51, 54, 55].

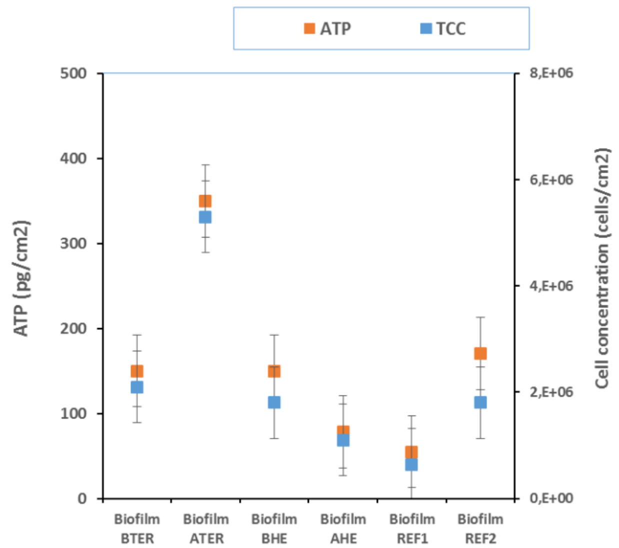

Figure 10. Biofilm development in DWDS 1 (BTER: before thermal energy recovery; ATER: after thermal energy recovery), DWDS 2 (BHE: before heat exchanger; AHE: after heat exchanger), DWDS 3 (REF1: at start of DWDS; REF 2: at end DWDS) (n=1)

The different results found for bulk water and biofilm phases are probably due to the big difference in their exposure time to higher temperature (one minute for bulk water and eight months for biofilm). The increased growth of biofilm after cold recovery may lead to a change in microbial community composition and structure. This preliminary research only lasted for a period of eight months. On the longer term a changed microbial community composition may affect the microbial water quality in the bulk water phase.

5. Conclusions

Thermal energy recovery from drinking water, being one of the possibilities to recover energy from the water cycle, offers an alternative for the use of fossil fuel and thus contributes to the reduction of GHG emissions. Cold recovery, as will be applied in a specific case in Amsterdam, showed to reduce the GHG emission with 869 ton CO_2-eq/a and showed to have a positive business case: compared to a traditional system with cooling machines, TCO decreased from € 8.2 mln to € 6.8 mln. Although the total supply potential of cooling with drinking water and the total demand for cooling of non-residential buildings in Amsterdam seem balanced, projects have to be evaluated individually to judge their feasibility. Preliminary research at laboratory scale showed that the microbial drinking water quality, measured by TCC, ATP, *Legionella* spp. and *Aeromonas* spp., was not affected by cold recovery. However, biofilm formation increased after cold recovery and requires further research to reveal the potential role of enhanced biofilm growth on microbiological water quality.

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Highlights Energy Recovery from the Water Cycle: Thermal Energy from Drinking Water

- Thermal energy can be recovered from drinking water
- Both heat and cold can be recovered from drinking water
- Cold recovery did not affect the microbiological water quality negatively
- Cold recovery reduced GHG emissions with 90%
- Cold recovery showed a 17% lower TCO compared with traditional cooling