EXPLORING THE TECHNICAL AND ECONOMIC FEASIBILITY OF USING THE URBAN WATER SYSTEM AS A SUSTAINABLE ENERGY SOURCE

by

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The objective of this paper is to determine the technical and economic feasibility of an alternative energy system in which the urban water system functions as a source for sustainable energy supply. It is demonstrated that aquifer thermal energy storage supplemented with surface water heat collection in summer, yields sufficient heat to compensate total heat demand of a residential district. Using the urban water system as energy source makes natural gas supply obsolete, provides a CO_2 reduction of 60% and is preferable in terms of costs compared to conventional gas based central heating installations. The feasibility of the urban groundwater system, urban surface water system, and the economic feasibility are determined in this paper. The local groundwater feasibility to supply the design discharge is determined by soil and aquifer characteristics from the national groundwater database, reference projects, and bore-hole data. A heat balance model is used to quantify effects on the water system. Internal rate of return calculation for the investments and full lifetime exploitation costs are used to determine the economic feasibility of the concept. In summer, there is a net water temperature decrease of 1.5-1.6 °C. Water quality and ecological improvement take place because a lower temperature results in increasing oxygen content. Moreover, the expected water temperature increase by climate change can be prevented. The concept is economically feasible. Considering the full lifetime and all investment and exploitation costs, the concept is more profitable than a conventional system.

Key words*: sustainable energy, urban water, aquifer thermal energy storage*

Introduction

The need for a more sustainable, less vulnerable energy supply is nowadays widely acknowledged [1, 2]. Water offers many opportunities to contribute to a more sustainable energy supply. Possibilities include geothermal and aquifer energy systems [3, 4] and the use of water as a direct heat collector [5]. The combined use of groundwater and surface water as a heat storage and heat collection system has rarely been studied [6]. This paper reports on possibilities of this combination by describing a casestudy. In the Netherlands, buildings are mainly heated by conventional natural gas based central heating systems (CHS), most often on individual house scale. However, increasingly the use of aquifer thermal energy storage (ATES), for heating and cooling of buildings is applied. ATES is a concept in which the aquifer serves as a medium for temporary heat storage and cold storage. Heating and cooling is delivered by heat pumps to the building. The first project was realized in Dorigny, Switzerland, in 1982 and more pilots were started in Denmark (Hørsholm) and the USA (St. Paul, Minn.) [7]. The total number of ATES projects has grown rapidly. For instance, in 2005 there were over 400 finished ATES projects in the Netherlands [7]. Besides using the groundwater, the urban surface water system as a source for heat can be applied. The first project in Europe that is still functioning was finished in Zürich, Switzerland, in 1938. Here, the Rathaus building extracts heat and cold from the Limmat river. A proposal to investigate the capacity of using the Amsterdam canal system to heat new urban districts was made in 1946 [8]. However, this investigation was never made because of the abundance of natural gas at the time. The recent urgency to find renewable energy sources has put the urban surface water back on the map of energy sources in the Netherlands. Recently, projects were finished in the cities of Den Bosch and Den Haag and another project is proposed in Rotterdam. This research investigates the possibility of combining the potential of surface water systems and groundwater systems (ATES) as an energy source.

Benefits of ATES are: a very high efficiency, a high level of comfort, and a considerable amount of CO_2 reduction [9]. Although ATES is used more and more in the Netherlands, the system still has its limitations. Application of the system requires long term aquifer heat equilibrium to prevent structural aquifer temperature change. Therefore, ATES is mainly used in office buildings in which heat demand is comparable to cooling demand on a yearly timescale. In other buildings, such as residential buildings, ATES is used less frequently because heating demand tends to be much higher than cooling demand. In that case, application of ATES results in a structural aquifer temperature decrease. To increase feasibility of ATES in residential districts, expanding it with a heat collection system (ATES+) by extracting heat from surface water for aquifer regeneration is a promising option. In the municipality of Heerhugowaard in the northern part of the Netherlands, a new urban district of 2816 houses, De Draai, will be developed. The ambition of the municipality Heerhugowaard is to give the urban water system more economic value. Moreover, the municipality aims to become the first municipality in the Netherlands that achieves a CO_2 neutral emission status. For that purpose, ATES+ is compared to a conventional system (CS) on CO_2 reduction, water system effects, and cost effectiveness.

With ATES groundwater is extracted from an aquifer. In winter, when heating is needed, heat is extracted from groundwater. The extracted heat is transferred to the working fluid in the heating system of the house. By using a heat pump, the working fluid in the low temperature heating (LTH) system obtains a temperature of 35-50 °C. Groundwater at the same time is cooled down a number of degrees and infiltrated back into the aquifer. The left part of fig. 1 elaborates this. During summer, the system works in the opposite way. Heat surplus in houses is extracted by cold groundwater, and groundwater of higher temperature is infiltrated in the aquifer. No negative effects occur as long as the amount of extracted heat to the aquifer is the same as the amount of supplied heat to the aquifer on a long timescale.

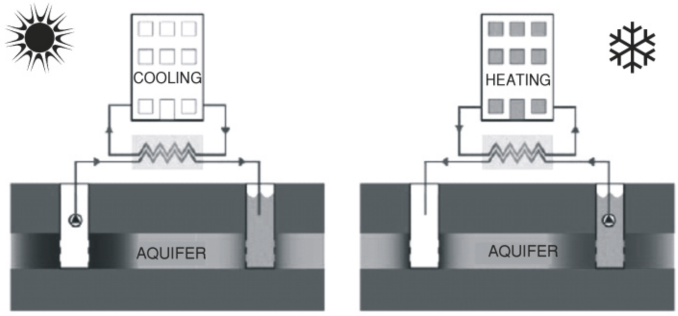

Figure 1. Aquifer thermal energy storage in summer (left) and winter (right) [2]

The ATES system is supplemented with a surface water heat collection system (ATES+) in order to obtain heat equilibrium on a yearly timescale. The required amount of heat will be extracted from the urban water system in the three summer months, when the temperature is highest. During these months, water quality problems occur that result from eutrophication. These problems are aggravated by high water temperature. ATES+ could have a positive influence on these problems because it will decrease surface water temperature. Water is pumped from the surface water system. In a heat exchanger heat is transferred from surface water to groundwater. Surface water is cooled down and groundwater is heated. Subsequently, cooled water is discharged to the surface water and groundwater with increased temperature is infiltrated. This causes a continuous heat flux from surface water to groundwater which regenerates groundwater with heat and recovers aquifer heat equilibrium on a yearly base. Figure 2 illustrates the concept.

Methods

To determine the technical and economic feasibility of the water system as a sustainable energy source (ATES+), a couple of steps are taken. First, energy demand and CO_2 emission of the new residential district are calculated. Heat and cooling will be supplied to houses by use of ATES+. The yearly difference between heating and cooling demand determines the aquifer heat shortage. Second, feasibility of the local geohydrological situation is determined by analysing previous surveys and bore-hole data. Third, temperature effects and oxygen content effects on the surface water system are determined. Fourth, the economic feasibility is determined, climate aspects are investigated, and a comparison with CS is made.

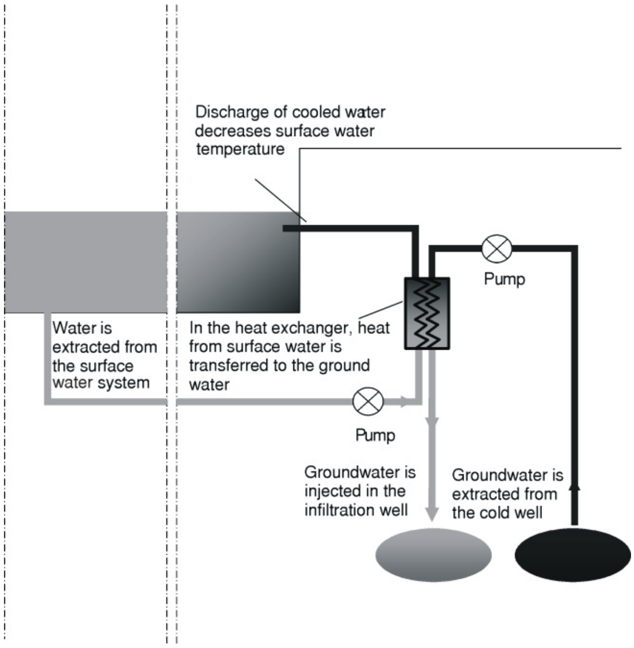

Figure 2. Regeneration of aquifer by surface water heat

Heat demand estimation method

Heating and cooling in houses is used for indoor climate control and heating of tap water. Heat demand is determined by the quality of insulation, typology of the house, and regional climate conditions. The Dutch government has issued standards for insulation, the energy performance coefficient (EPC). For new houses the EPC should be equal or lower than 0.8. The typology of the houses in De Draai consists of 19 different types, ranging from single apartments to one family houses. These houses have been classified according to five reference house types of SenterNovem [10]. Reference houses have standardized energy demands and CO_2 emissions that are used to calculate heat demand. These figures are based on Dutch climate conditions, housing data and the Dutch national energy infrastructure including the natural gas distribution system and the electricity grid. In this research, reference houses are used to calculate energy demand and CO_2 emissions in the CS and ATES+ system in order to enable comparison. The CO_2 reductions for ATES+ are calculated based on prevented natural gas use. To determine the required maximum heating capacity and cooling capacity for houses P_h and facilities P_S, eqs. (1) and (2) are used [11]:

$$P_{\mathrm{h}} \quad f_{\mathrm{co}} n P_{\mathrm{max\,ah}} \tag{1}$$

$$P_{\mathrm{S}} \quad \frac{H_{\mathrm{y}}}{t_{\mathrm{fl}} 3600} \tag{2}$$

The maximum required groundwater extraction is determined by the heating and cooling capacity, the temperature difference and the coefficient of performance (*COP*) of the heat pump. It is given by eq. (3) [11]:

$$Q_{\mathrm{gw\,max}} \quad \frac{3600(P_{\mathrm{h}} \quad P_{\mathrm{S}})\ 1 \quad \dfrac{1}{COP}}{c_{\mathrm{w}} \Delta T \rho_{\mathrm{w}}} \tag{3}$$

Groundwater feasibility method

No net extraction of groundwater takes place, only extraction of heat. The local groundwater feasibility to supply the design discharge is determined by soil and aquifer characteristics (type, profile, quality) and available space to locate bore-holes for extraction and infiltration. Soil and aquifer data are from the groundwater map of the Netherlands [12], data on four bore-holes information from the geohydrological database REGIS [13] and from the national geological DINO database [14]. Space is needed to locate bore-holes for extraction and infiltration of the required design discharge. The number of bore-holes is determined by the maximum allowable bore-hole velocity, bore-hole diameter, and permeability. For infiltration, the maximum allowable bore-hole groundwater velocity is given by eq. (4) that is based on the work of Buik *et al.* [15]. The membrane filtration index (*MFI*) gives the specific clogging capacity of the groundwater [sl^{-2}] in terms of how much time is required for a liter of water to flow trough the filter and how this number increases with each liter of water. With the specific clogging velocity v_{cl} of the groundwater, permeability k, and the full load equivalent of the heat pump, the maximum allowable velocity on the bore-hole is given by eq. (4):

$$v_{\mathrm{max}} \quad 1000 \ \frac{k}{150}^{0.6} \sqrt{\frac{v_{\mathrm{cl}}}{2 MFI t_{\mathrm{fl}}}} \tag{4}$$

For extraction, the maximum allowable bore-hole velocity is given by eq. (5) [11]:

$$v_{\mathrm{max}} \quad \frac{k}{12} \tag{5}$$

The maximum allowable velocity on the bore-hole, bore-hole radius r and the maximum required groundwater extraction determine the total required filter length h which can than be calculated by eq. (6):

$$v_{\mathrm{max}} \quad \frac{Q_{\mathrm{gw\,max}}}{2\pi r h} \tag{6}$$

Surface water heat balance method

Two types of water system effects are distinguished: temperature effects and oxygen content effects. To quantify temperature effects on the surface water system, a heat balance spreadsheet model on a monthly base is made. The main purpose of this research is to quantify the capacity of surface water to supply heat to the groundwater in order to achieve aquifer heat equilibrium on yearly basis. For that purpose a heat balance is used to quantify surface water temperature effects resulting from heat extraction. The heat balance of a water body is given by eq. (7) [16]:

$$H_{\mathrm{tot}} \quad H_{\mathrm{sl}} \quad H_{\mathrm{a}} \quad H_{\mathrm{l}} \quad H_{\mathrm{e}} \quad H_{\mathrm{c}} \quad H_{\mathrm{f}} \tag{7}$$

Solar radiation

The sun is constantly heating the earth and water surfaces. Direct solar radiation is referred to as short wave radiation (wavelength <4 m). Only a part of the incoming solar radiation eventually reaches the earth because of clouds, dust particles, and reflection. There are many empirical relations to describe the relation between incoming solar radiation and net solar radiation. However, since the net solar radiation in the Netherlands is measured by the Royal Meteorological Agency [17], these measurements are used as an input for the model.

Atmospheric radiation

Solar radiation causes heating of the atmosphere that subsequently results in atmospheric elements emitting (long wave) atmospheric radiation. The amount of radiation emitted from these elements is determined by the temperature, cloud density and vapour pressure. The law of Stefan-Boltzmann gives the following general relation:

$$H_{\mathrm{a}} \quad \varepsilon\sigma_{\mathrm{SB}}(T_{\mathrm{a}} \quad 273)^4 \tag{8}$$

The emissivity ε varies considerably depending on the condition of the atmosphere. The following expression (9) for emissivity was proposed by Edinger [18] that was based on the work of Brunt [19]:

$$\varepsilon \quad a \quad b\sqrt{p_{\mathrm{a}}} \tag{9}$$

in which a and b are constants that depend on air temperature, and the ratio of measured atmospheric radiation, and the theoretical atmospheric radiation. The atmospheric vapour pressure is given by eq. (10) [20]:

$$p_{\mathrm{a}} \quad 6.112 \quad 10^{\frac{7.5T_{\mathrm{a}}}{273.7 \quad T_{\mathrm{a}}}} \tag{10}$$

Several researchers have investigated the coefficients in Brunt's formula. Table 1 provides an overview [21]. For Dutch circumstances, the following relation (11) has been proposed by Wiggers [22]. In this formula the emissivity is a function of cloud coverage and atmospheric vapour pressure:

$$\varepsilon \quad 0.74(1 \quad 0.17C_{\mathrm{c}}) \quad 0.0045(1 \quad C_{\mathrm{c}})p_{\mathrm{a}} \tag{11}$$

This relation is comparable with the Brunt formula [20], the emissivity difference under Dutch circumstances is less than 3%.

Table 1. Overview of Brunt's coefficients [21]

Investigator	Location	a	b [Pa$^{-1/2}$]
Brunt (1932)	Benson (UK)	0.55	0.065
Monteith (1961)	Kew (UK)	0.53	0.065
Swinbank (1963)	Australia	0.64	0.037
Sellers (1965)	22 locations world wide	0.61	0.048
Berger *et al*. (1984)	France	0.66	0.040
Bergdahl and Martin (1984)	Six locations in the USA	0.56	0.059
Heitor *et al*. (1991)	Lisbon (Portugal)	0.59	0.044
Iziomon *et al*. (2003)	Bremgarten (Germany)	0.6	0.064
Iziomon *et al*. (2003)	Feldberg (Germany)	0.5	0.066

Back radiation of lake

The back radiation of the lake is the heat emitted from a water body. The process can be phycially described by the law of Stefan-Boltzman, the only determining factor is the water temperature T_w and in this case $\varepsilon = 0.97$ [16, 22, 23]. The resulting heat flow is presented in eq. (12):

$$H_1 \quad \varepsilon\sigma_{SB}(T_w \quad 273)^4 \tag{12}$$

Evaporation heat flux

By the process of evaporation, heat is extracted from surface water. By condensation heat will be delivered to the surface water. The evaporation flux is determined by a wind velocity function and the difference between the actual vapour pressure and the saturation vapour pressure. The following expression (13) describes the heat extraction resulting from evaporation [16]:

$$H_e \quad f(v_{wind})(p_s \quad p_a) \tag{13}$$

There are many empirical approximations of the wind velocity function in different regions. An overview is presented in Boderie [20]. The formula of the World Meteorological Organization [24] has a good applicability for moderate climates [25]. For the saturation vapour pressure many good approximations are available that yield almost identical results [20]. The wind function and saturated vapour pressure are computed as:

$$f(v_{wind}) \quad 3.68 \quad 2.65\, v_{wind} \tag{14}$$

$$p_s \quad 23.4 \;\; 1.062^{T_w \quad 20} \tag{15}$$

Conduction heat flux

The conduction heat flux, or sensible heat flux, is the heat flux that is driven by the temperature differences between the water temperature and the air temperature. Bowen [26] found that heat conduction and evaporation heat flux are proportional with Bowen ratio B. A general expression is given by eqs. (16, 17). The Bowen ratio is determined by the psychometric contant γ and the difference between water temperature and air temperature, and the difference between saturation vapour pressure and atmospheric vapour pressure:

$$H_{\mathrm{c}} \quad BH_{\mathrm{e}} \tag{16}$$

$$B \quad \gamma \frac{T_{\mathrm{w}} \quad T_{\mathrm{a}}}{p_{\mathrm{s}} \quad p_{\mathrm{a}}} \tag{17}$$

Substituting eqs. (14, 16, 17) in eq. (13) gives the following expression for conduction heat flux:

$$H_{\mathrm{c}} \quad (2.02 \quad 1.46 v_{\mathrm{wind}})(T_{\mathrm{a}} \quad T_{\mathrm{w}}) \tag{18}$$

Heat pump extraction flux

An additional heat balance component in this case is extraction of heat from surface water. This amount is equal to the total annual required regenerated heat demand divided by the amount of extraction days divided by the total surface of the water system. Equation (19) presents the relation:

$$H_{\mathrm{hp}} \quad \frac{(P_{\mathrm{h}} \quad P_{\mathrm{S}})_{\mathrm{heating}} \quad (P_{\mathrm{h}} \quad P_{\mathrm{S}})_{\mathrm{cooling}}}{24 \quad 3600\, dA_{\mathrm{sw}}} \tag{19}$$

Because the water system under consideration is a closed system, heat flux H_{f} resulting from inflowing and outflowing water in the system is equal to zero. In the heat balance components, only surface water radiation, evaporation heat flux, and heat conduction are (partly) determined by water temperature. Because all other factors are known, the surface water equilibrium temperature can be calculated iteratively by a spreadsheet model for a situation where heat is extracted (ATES+) and in a situation where no extraction takes place (CS). Table 2 summarizes the heat balance components.

Oxygen content effects

By extracting heat from the surface water system, water temperature is decreased. Physical reparation is the flux of oxygen from the atmosphere to the surface of the water system. Reaeration is determined by the oxygen deficit: the difference in saturation oxygen content and the actual oxygen content. The saturation oxygen content depends on the water temperature. Phys-

Table 2. Heat balance components

Component [Wm^{-2}]	Method
Solar radiation	Average of nearest weather stations, De Kooy and Schiphol
Atmospherical radiation	$H_{\mathrm{a}} = \varepsilon \quad _{\mathrm{SB}} (T_{\mathrm{a}} + 273)^4$
Lake radiation	$H_{\mathrm{l}} = -\varepsilon \quad _{\mathrm{SB}} (T_{\mathrm{a}} + 273)^4$
Evaporation and condensation heat flux	$H_{\mathrm{e}} = (3.68 + 2.65\, v_{\mathrm{wind}})(p_{\mathrm{a}} - p_{\mathrm{s}})$
Heat conduction to/from atmosphere	$H_{\mathrm{c}} = (2.02 + 1.46\, v_{\mathrm{wind}})(T_{\mathrm{a}} - T_{\mathrm{w}})$

ical reaeration is determined by the oxygen deficit and the physical reaeration coefficient, it is described by eq. (20) [27]:

$$\frac{\mathrm{d}D}{\mathrm{d}t} = -k_2 D \tag{20}$$

Because the physical reaeration coefficient k_2 is constant for small temperature changes, the increase in oxygen flux is proportional to the increase in oxygen deficit D. Further increase of oxygen flux can be expected by an increased surface water circulation velocity. This will be caused by extracting and discharging water for heating and cooling purposes. Equation (21) describes that the physical reaeration coefficient will increase with the canal flow circulation velocity that results from water discharge to the system [25, 28]:

$$k_2 \propto v^{3/8} \tag{21}$$

Economic feasibility method

To compare the combined cost of investments and exploitation various methods are available. Calculation of the net present value (*NPV*) and internal rate of return (*IRR*) are often used for this purpose. The *NPV* discount future expenditures and income X in year T to their present value [29], the relation is expressed by eq. (22):

$$NPV = \sum_{t=0}^{T} \frac{X_\mathrm{t}}{(1+i)^t} = \frac{X_0}{1} + \frac{X_1}{1+i} + \frac{X_2}{(1+i)^2} + \ldots + \frac{X_T}{(1+i)^T} \tag{22}$$

The *IRR* indicates at which discount rate a project becomes profitable. The discount rate at which the *NPV* of a project is zero is equal to the *IRR*. The higher the *IRR* the more feasible a project is from an economic point of view because in that case the project can be executed by even a very high discount rate. The *IRR* can be determined by iteration in eq. (23) [29]:

$$\sum_{t=0}^{T} \frac{X_\mathrm{t}}{(1+IRR)^t} = NPV = 0 \tag{23}$$

A comparison is made between a CS with gas based central heating and the system in which the water system is the source for sustainable energy (ATES+). For this comparison, the investment and exploitation costs of the total system are taken into account including, extraction and infiltration, distribution and the heat pump installation at household level.

Design specifications, constants, and assumptions

To be able to determine the feasibility of the concept design specification were obtained from the technical consultants that have designed the system. For other factors, assumptions are made for heat demand, groundwater, surface water, and economic aspects based on reference projects and analysis of the local situation. Design specifications (DS), constants (C), and assumptions (AS) are summarized in tabs. 3-5. Design specifications were obtained from the system engineers that collaborated in this research. Furthermore, the water system is assumed to behave like a fully mixed system, because the water system in De Draai consists of connected small lakes in which mixing circulation pumps are installed. Monthly water temperature is assumed constant. In reality, water temperature fluctuations around the average occur,

Table 3. Design specifications and assumptions for heating demand and groundwater

Heating demand	Unit		Type
Full load equivalent	Hours	1200	DS
Coefficient of performance (*COP*)	–	4.7	DS
Max heating power average single house	kW	7	DS
Max cooling power average single house	kW	3	DS
T groundwater	°C	6	DS
Groundwater			
Specific clogging density	m per year	0.1	AS
MFI	sl^{-2}	2	AS

Table 4. Design specifications, constants, and assumptions for surface water

Surface water	Unit		Type
Extraction discharge	m^3s^{-1}	0.4	DS
Heat capacity of water	$kJkg^{-1}°C^{-1}$	4.18	C
Specific density of water	kgm^{-3}	1000	C
Average oxygen content	mgl^{-1}	5	AS
Constant of Stefan-Boltzman	$Wm^{-2}K^{-4}$	$5.67\ 10^{-8}$	C
Emissivity ε of the water system	–	0.97	C

however, these do not affect the monthly heat balance and the influence of heat extraction on the average water temperature. Heat sources that are neglected in the heat model are turbulence, transport by precipitation, heat conduction to and from the bed sediments and biological and chemical degradation processes. However, the contribution of these processes to the equilibrium temperature is only small [16, 25].

Table 5. Design specifications and assumptions for economy

Economy	Unit		Type
Discount rate	%	6	AS
Inflation	%	2	AS
Electricity annual price increase	%	3	AS
Natural gas annual price increase	%	5	AS
Technical life time household installation	year	15	DS
Technical lifetime distribution network	year	30	DS

Results

Heat demand and CO_2 emission

Table 6 gives the heat demand, required heating and cooling power of the total residential district. This determines total groundwater extraction, yearly groundwater extraction and yearly heat shortage of the aquifer. Moreover, CO_2 emissions are presented. As can be observed, ATES+ has an annual CO_2 emission of 2750 tons compared to 6750 tons in case of a conventional system; this is equal to a CO_2 reduction of 60%.

Groundwater feasibility

The local soil profile is schematised in tab. 7. Further analysis of local data shows that the separating layer between the first and the second aquifer is absent at the location of De Draai. Permeability is about 20 m per day. Moreover, the first aquifer is brackish, gradually changing to salt from a depth of 40 meters. Therefore, the first and second aquifer from a depth of 20 up to

Table 6. Heat demand, groundwater extraction and emissions

	Unit	Heating	Cooling
Number of houses	–	2,816	
Total demand	GJ per year	106,657	21,331
Emission CS	10^3 kg per year	6,750	
Emission ATES+	10^3 kg per year	2,750	
Yearly heat shortage aquifer	GJ per year	85,325	
Correction factor	–	0.9	0.9
Total power	kW_t	18,776	8,047
Max. groundwater extraction	m^3 per hour	2,119	1,155
Total groundwater extraction	m^3 per year	25,43,210	1,386,060

60 meter can be used for placing filters to extract and infiltrate water. Mixing of fresh and brackish water will not occur because there is no fresh water in the extraction zone. No occurrence of mixing is a precondition for obtaining legal permission for the heat pump concept in the Netherlands. Space is needed to locate bore-holes for extraction and infiltration of the required design discharge. The number of bore-holes is determined by the maximum allowable bore-hole velocity, bore-hole diameter and permeability. The available area of 1.500.000 m^2 is sufficient to locate 14 wells with mutual distance of 225 m. Table 8 summarizes the results.

Table 7. Schematised regional and local soil profile

Regional situation				Local situation	
Depth under terrain level [m]	Soil types	Geological formation	Soil layer	Depth under terrain level [m]	Soil types
0-(15 to 20)	Fine sand, clay, and peat	Westland	Covering layer	0-4	Moderate fine sand and sandy clay
				4-(15 to 20)	Moderate fine to moderate coarse sand
(15 to 20)->120	Moderate to coarse sand	Twente, Kreftenheye, Drente, Eem, Urk, Sterksel	First and second aquifer	(15 to 20)-35	Moderate coarse to coarse sand
				35-37	Sandy clay
				37->60	Moderate fine to moderate coarse sand

Surface water feasibility

Table 6 shows that the yearly heat shortage in the aquifer under the residential district is 85,325 GJ. This is the amount that will have to be extracted from the urban surface water system. Results from the heat balance model enable comparison between CS and ATES+. As a result, evaluation of the net temperature decrease is possible. Tables 9 and 10 show the temperature decrease that results from heat extraction is 1.5 to 1.6 °C. The corresponding oxygen saturation con-

Table 8. Required filter length and number of wells

Design extraction	m^3 per hour	2,119
Maximum allowable extraction velocity	m per hour	1.7
Maximum allowable infiltration velocity	m per hour	4.5
Total filter length	m	495
Required number of wells	couples	14
Mutual distance wells	m	225
Required surface	m^2	1,438,000

Table 9. Surface water temperature results of a conventional system

	Unit	June	July	August
Solar radiation	Wm^{-2}	203.3	193.9	166.5
Atmospherical radiation	Wm^{-2}	312.3	337.7	338.4
Lake radiation	Wm^{-2}	–388.5	–400.9	–397.1
Evaporation	Wm^{-2}	–105.4	–109.2	–94.3
Conduction	Wm^{-2}	–21.1	–21.0	–13.2
Heat extraction	Wm^{-2}	0	0	0
Water temperature	°C	16.9	19.2	18.5
Oxygen saturation content	mgl^{-1}	9.6	9.3	9.4
Oxygen deficit	mgl^{-1}	4.6	4.3	4.4
Circulation discharge	ms^{-3}	0.0	0.1	0.1

tent increases. Two driving forces determine the physical reaeration flux (1) the oxygen deficit, and (2) the flow velocity. In case of a oxygen content of 5 mg/l, the oxygen deficit increases with 8.7% in June, 4.6% in July, and 4.7% in August. The extraction and discharge of water for heating and cooling results in a twofold increase of circulation flux compared to CS in which only a circulation pump is installed. This causes a proportional increase in flow velocity. Consequently, physical reaeration increases with 36 to 41%, following eq. (21).

Table 10. Surface water temperature results of the ATES+ system and a comparison

	Unit	June	July	August
Solar radiation	Wm^{-2}	203.3	193.9	166.5
Atmospherical radiation	Wm^{-2}	312.3	337.7	338.4
Lake radiation	Wm^{-2}	–378.0	–392.8	–388.5
Evaporation	Wm^{-2}	–75.7	–77.8	–62.8
Conduction	Wm^{-2}	–6.42	–7.61	0.88
Heat extraction	Wm^{-2}	–52.9	–52.9	–52.9
Water temperature	°C	15.3	17.7	16.9
Oxygen saturation content	mgl^{-1}	10	9.5	9.7
Oxygen deficit	mgl^{-1}	5	4.5	4.7
Circulation discharge	ms^{-3}	0.2	0.2	0.2
Comparison (ATES+ vs. CS)				
Net temperature decrease	°C	1.6	1.5	1.6
Oxygen deficit increase	%	8.7	4.6	4.7
Increase k_2	%	30	30	30
Total physical reaeration increase	%	41	36	39

Economic feasibility

The investment costs of the ATES+ are considerably higher. However, the exploitation costs are lower because of energy savings. Figure 3 shows the *NPV* of ATES+ is lower than the *NPV* of the conventional system. After 30 years of

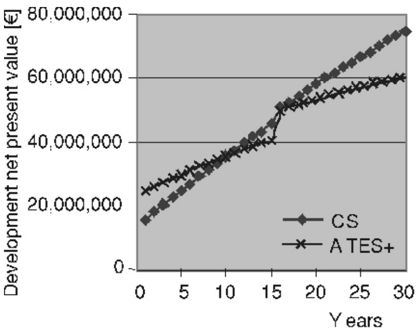

Figure 3. Net present value of the two systems

technical lifetime the difference in costs is 20%. Also the *IRR* calculations are positive for the ATES+. The *IRR* is 15% at the end of the technical lifetime. This means that the project is feasible at a discount rate of 15%.

Discussion

Potential and applicability

The results show that application of ATES+ in De Draai is preferable to CS based on water system effects, cost effectiveness and CO_2 emission. ATES+ makes the construction a natural gas distribution network obsolete in a new urban development. Therefore, the district does not rely on international gas distribution networks that might be disrupted in the future by geopolitical tensions, incidents, or terrorism. However, still electricity is needed for operating the system. Recent climate impacts research on surface water systems, indicate that climate change will result in an increase of 0.8 to 2.8 °C in the Netherlands [30]. This will cause increased water quality problems, such as anaerobic conditions and eutrophication. Decreasing the water temperature by using ATES+ potentially mitigates effect of climate change on urban surface water systems.

Although the feasibility of the ATES+ concept has been demonstrated for one residential project in the Netherlands, it is applicable elsewhere. Considering the fact that more than 85% of the Netherlands is suitable for aquifer heat storage and new developments have an increasing amount of surface water, this concept has high potential. In an international context this concept has potential for cities in alluvial plains where aquifers have been formed and surface water such as lakes, rivers, or canals are present.

Limitations and obstacles

Limitations of the results can be subdivided in water system effects and economic effects. For groundwater feasibility, assumptions have been made for the specific clogging velocity and *MFI*. These assumptions are based on comparable projects in the Netherlands and haven been used to calculate the critical infiltration velocity. The assumptions made in tab. 3 are conservative design standards. For instance, *MFI* is generally below 2 s/l^2 in Dutch circumstances [31], whereas the specific clogging velocity is generally higher than 0.1 m per year. As a result, the required surface in tab. 8, is a upper bound estimate.

The assumption made in tab. 4 with regard to the actual oxygen content corresponds with the minimum target level of the local water board in correspondence with the European Water Framework Directive [32].This is a lower bound assumption: higher oxygen content will result in a higher relative increase of the oxygen deficit by decreasing the temperature. Table 10 indicates that physical reaeration increases with 36 to 41% by applying ATES+. This will have beneficial effects on water quality. However, conclusions about the resulting oxygen content cannot be made within the scope of this research. To estimate oxygen levels, a detailed water quality investigation should be undertaken in follow up research that includes biological reaeration processes in addition to physical processes.

The economic assumptions are based on conservative estimates. For instance, the annual natural gas price is assumed to be 5%. Over the past 10 years, the gas price in the Netherlands has risen with an average of 8% and electricity with 7% [33]. Considering the expected lifetime of the system and the unknown energy price development in the future, rather safe assumptions have been made. However, with the current global surge in energy prices, the long term economic feasibility of the ATES+ system is probably more favourable than is reported here.

An obstacle for large scale implementation of this concept is the rather high investments costs. Although the exploitation costs are considerably lower because of energy savings, only residents benefit from this, whereas project developers face higher investment costs. As a result, project developers are not likely to contribute to wide scale application of the system. A possible solution could the commercial exploitation of the system by an energy utility company. Given the high *IRR* of the system, there is certainly a commercially attractive potential.

Another factor preventing application on a wider scale are competing alternatives, more established, sustainable energy options such as asphalt solar collectors, biomass installations or collective systems that supply surplus heat from industrial areas and waste incinerators. For these systems, subsidies from the government are already available. The ATES+ concept does not have this benefit.

Conclusions

This paper has demonstrated that a new residential district in the Netherlands can be self reliant for heating and cooling purposes by aquifer thermal energy storage supplemented with surface water heat collection (ATES+). By cooling the surface water with 1.5-1.6 °C in three summer months, enough heat is collected to compensate full residential heating and cooling demand. This makes sustainable energy supply by aquifer thermal energy storage (ATES) possible in residential areas. Until now, this system has mainly been applied in office buildings. With the concept of ATES+, fossil fuels are no longer required to heat houses, although electricity remains necessary to operate the system. Considerable energy savings and a CO_2 emission reduction of 60% are achieved. Water quality and ecological improvement take place because a lower temperature results in increasing oxygen content. Moreover, expected water temperature increase by climate change can be prevented. The concept is also economically feasible. Considering the full lifetime and all investment and exploitation costs, the concept is more profitable than a conventional system. Therefore, this concept has the potential to contribute to the societal objective to achieve a more sustainable, self-reliant energy supply.

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Nomenclature

A_{sw} – total area of surface water, [m^2]
B – Bowen ratio, [–]
C_c – cloud coverage as a fraction of 1, [–]
COP – coefficient of performance, [–]
c_w – heat capacity of water, [$Jkg^{-1}{}^\circ C^{-1}$]
D – oxygen deficit, [mgl^{-1}]
d – total period surface water heat pump operation, [days]
f_{co} – correction factor, [–]
$f(v_{wind})$ – empirical wind velocity function, [$Wm^{-2}HPa^{-1}$]
H_a – incoming atmospheric radiation, [Wm^{-2}]
H_c – conduction heat flux, [Wm^{-2}]
H_e – evaporation heat flux, [Wm^{-2}]

H_{f} – heat flux resulting from inflowing and outflowing water in the system, [Wm^{-2}]
H_{hp} – heat pump extraction flux, [Wm^{-2}]
H_{l} – back radiation of lake, [Wm^{-2}]
H_{ss} – incoming net solar radiation, [Wm^{-2}]
H_{t} – net change of heat per unit of area, [Wm^{-2}]
H_{y} – total yearly service heating demand, [kJ]
h – total filter length, [m]
IRR – internal rate of return, [–]
i – discount rate, [–]
k – permeability, [m per day]
k_2 – physical reaeration coefficient, [d^{-1}]
MFI – membrane filtration index, [sl^{-2}]
NPV – net present value, [€]
n – number of houses, [–]
p_a – atmospheric vapour pressure, [Pa]
P_{h} – maximum total heating power for houses, [kW]
$P_{max\ ah}$ – maximum heating power average house, [kW]
P_{S} – maximum total heating power for services, [kW]
p_{s} – saturation vapour pressure, [Pa]
$Q_{gw\ max}$ – maximum groundwater extraction, [m^3h^{-1}]
q_{r} – required extraction per kW, [$m^3h^{-1}kW^{-1}$]
r – radius of bore-hole, [m]
T_{a} – air temperature, [°C]
T_{w} – water temperature, [°C]
T – temperature difference groundwater, [°C]
t – time
t_{fl} – full working load equivalent, [hours]
v – circulation velocity of canal flow, [ms^{-1}]
v_{cl} – specific clogging velocity, [m per year]
v_{max} – maximum allowable velocity on bore-hole, [m per year]
v_{wind} – wind velocity, [ms^{-1}]
X_{t} – income or expenditure in year t, [€]

Greek symbols

ε – emissivity of the atmosphere, [–]
γ – psychometric constant, [0.55 $hPaK^{-1}$]
ρ_{w} – specific density of water, [kgm^{-3}]
σ_{SB} – constant of Stefan-Boltzmann, [$Wm^{-2}K^{-4}$]

Subscript

a – atmospheric
c – conduction
cl – clogging
co – correction
e – evaporation
f – flow
fl – full load
gw max – maximum groundwater extraction
h – houses
hp – heat pump
l – lake
max – maximum
max, ah – maximum annual heating
S – services
s – saturation
SB – Stefan-Boltzmann
sl – solar
sw – surface water
t – time
tot – total
w – water
y – year

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