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Economic and environmental evaluation of different operation alternatives to aquifer thermal energy storage in Tehran, Iran

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Abstract. Aquifers are underground porous formations containing water. Confined aquifers are surrounded by impermeable layers on top and bottom, called cap rocks and bed rocks. A confined aquifer with a very low groundwater flow velocity was considered to meet the annual cooling and heating energy requirements of a residential building complex in Tehran, Iran. Three different alternatives of Aquifer Thermal Energy Storage (ATES) were employed to meet the heating/cooling demands of the buildings. These alternatives were using ATES for: cooling alone, heating alone by coupling with flat-plate solar collectors, and cooling and heating by coupling with a heat pump. For the economic evaluation of the alternatives, a life cycle cost analysis was employed. For the environmental evaluation, Ret Screen software was employed. For the considered 3 operational alternatives, using ATES for cooling alone had the minimum payback period time of 2.41 years and the life cycle cost of 16000 $. In the environmental perspective, among the 3 alternatives, coupling of ATES with heat pump for cooling and heating had the minimum CO_2 generation, corresponding to 359 tons/year.

1. Introduction

Nowadays, 40% of energy consumption and greenhouse gas (GHG) emissions of developed economies are related to buildings and 55% of building energy usage is for heating and cooling. The reduction of building-related GHG emissions is a high international policy priority. Since there are many technical solutions, these policies should involve significant improvements in the use of highly energy-efficient systems [1].

To reduce the energy consumption and the emission of GHG, the building sector needs energy efficient solutions operating at the lowest cost.

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In relation with energy and buildings, sustainable engineering requires:

1. Reduction of the heating and cooling energy needs of buildings to their minimum possible values;
2. Reduction of consumption of primary sources of energy to meet these minimum values through innovative designs of energy conversion systems and the employment of innovative methods to meet the energy demands.

Seasonal storage of thermal energy in aquifers and the utilization of solar energy and heat pumps are examples of innovative approaches to reduce primary energy demand for heating and cooling of buildings. Furthermore, ATES is technically and economically feasible [2-4].

Recently, ATES has become more popular, considering the problems caused by the depletion of fossil fuels and the increase of global warming [5,6]. Aquifer Thermal Energy Storage (ATES) systems are generally considered to be economically viable for the seasonal storage of thermal energy. In an ATES, contamination and depletion of groundwater are minimal, since the water withdrawn from aquifer is circulated through a heat exchanger and it is immediately injected back into the aquifer though injection well(s) [7-9].

Sommer et al. [10] determined the thermal performance of large-scale application of ATES using a simplified hydrogeological model. They compared the different zonation patterns and determined the influence of well-to-well distances. The role of aquifer thickness, thermal radius, and heat loss through the upper and lower confining aquitards was discussed. Jeon et al. [11] conducted a sensitivity analysis of recovery efficiency in two cases of high-temperature ATES system with a single well to select key parameters. For a fractional factorial design used to choose input parameters with uniformity, they considered the optimal Latin hypercube sampling with an enhanced stochastic evolutionary algorithm. Then, the recovery efficiency was obtained using a computer model developed by COMSOL multiphysics. They concluded that key parameters varied with the experimental domain of hydraulic and thermal properties as well as the number of input variables. Bloemendal et al. [12] described what optimal and sustainable use of the subsurface would look like in relation to ATES systems. With simulations, they showed their impact on the subsurface and described the current way of dealing with these impacts in the Netherlands. They also considered self-organization and self-governance to improve the adoption and operation of ATES. Zeghicia et al. [13] assessed the suitability of using heat and cold storage in a single deep geothermal aquifer for district heating and cooling. They used an integrated modelling approach for evaluating the controls on the energy efficiency of High-Temperature Aquifer Thermal Energy Storage (HT-ATES). They also analyzed sensitivity of the system efficiency with respect to the main physical (density, viscosity, and longitudinal dispersivity) and operational (distance between warm and cold storage volumes, flow rates) design parameters.

In 2007, Sethia and Sharma [14] conducted an economic evaluation of an aquifer and its combination with a heat exchanger for heating and cooling of a greenhouse. The payback period in this project was 3.5 years. It was more economical than the conventional heating/cooling system, which had a payback period of 7 years. They also employed a thermo-economic analysis for the economic evaluation of the system [15]. Gaine and Duffy [16] employed a Life Cycle Cost (LCC) method in their economic analysis of a borehole thermal energy storage system. They considered capital and operational costs, and calculated the costs of the recovered energy for different scenarios. Vanhoudt et al. [17] monitored the performance of an aquifer thermal energy storage system in combination with a heat pump for heating, cooling, and the ventilation of air in a Belgian hospital for a period of three years. Furthermore, they conducted an economic analysis and showed an annual cost reduction of 54000 €, when compared with the basic case with the payback time of 3.9 years.

Zhua et al. [18] conducted a probabilistic life cycle cost analysis for a Ground Source Heat Pump (GSHP) based on Monte Carlo method. They found that, from a life cycle perspective, the GSHP option was more favorable than the conventional system. Hang et al. [19] evaluated the solar water heating systems for typical US residential buildings from the energy consumption, economic, and environmental points of view. They considered flat-plate and evacuated-tube solar collectors. Their results showed that the flat-plate solar water heating systems, using a natural gas auxiliary heating, had the best performance. Kegel et al. [20] conducted a life cycle cost analysis for several combinations of heat pumps with renewable sources under Canadian climatic conditions. Through optimization, and for a 20-year life cycle analysis, they found that a standard air source heat pump system was the most economical option for an energy-efficient house. However, to our knowledge, no previous investigation has proposed or assessed ATES from the economic and environmental points of view. Therefore, the sub-objectives of this research paper are multi-fold and include:

- Designing a suitable confined aquifer to meet the cooling and heating energy needs of a residential building complex located in Tehran, Iran;
- Providing a comprehensive numerical model of the aquifer thermal energy storage and thermodynamic evaluation;
- Considering three different operational alternatives in combination with ATES;
- Noting economic and environmental considerations of the different operational alternatives;
- Using LCC method for economic considerations.

2. Heating and cooling energy needs of the residential building complex

A residential complex, consisting of 10 four-story buildings, located in Pounak region of Tehran was considered. Each floor consisted of 4 small apartments. The total floor area of the residential complex was 12800 m^2.

Hourly cooling and heating energy needs of the buildings were estimated using the software HAP 4.41 (Carrier) [6]. The building needed heating in 4 months of the year, beginning on November 21, and cooling in 4 months, beginning on May 21. The peak heating and cooling loads were estimated to be 0.504 MW and 1.13 MW, respectively. The annual heating and cooling requirements of the complex were estimated to be 1.9 TJ and 8.7 TJ, respectively. Since the cooling requirement was much larger than that of the heating, we designed the ATES considering cooling requirement [6].

Presently, the heating and cooling needs of the buildings are met through gas-fired boilers, with supply and return hot water temperatures of 60 and 40°C, respectively. Vapor-compression system, employing an environmentally safe refrigerant, is employed for cooling, with supply and return chilled water temperatures of 7 and 15°C, respectively. Also, fan coils are employed in rooms for space heating and cooling.

3. Utilizations of ATES for cooling and heating of the buildings

We considered several alternatives to meet the heating and cooling energy requirements of the building complex. These alternatives were: direct cooling through ATES, coupling ATES with flat-plate solar collectors for heating, and finally coupling ATES with heat pump for both heating and cooling. These alternatives are briefly described below [6].

3.1. Direct cooling through ATES

In the ATES, water is withdrawn from the extraction well(s) in order to supply the thermal energy requirements of the building. In summer, cold water is withdrawn from the aquifer. It provides the cooling needs of the building by going through a heat exchanger. It is then injected back into aquifer through the injection well(s) and stored there for winter operation. In winter, water is withdrawn from the aquifer and it is cooled by going through a cooling tower and then injected back into the aquifer. Figure 1 shows the system operation in this alternative.

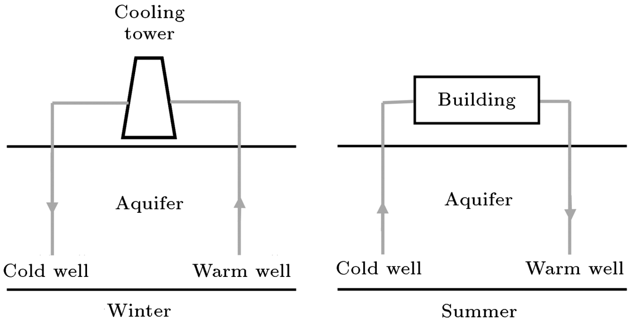

Figure 1. Direct Cooling through ATES.

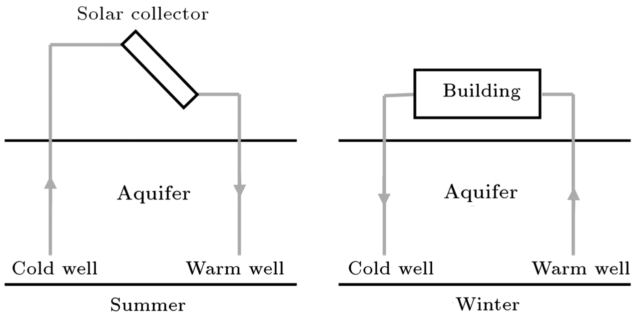

Figure 2. Heating by coupling of the ATES with flat-plate solar collectors.

3.2. Coupling ATES with flat-plate solar collectors for heating

Figure 2 shows an ATES, coupled with solar collectors. In this system, solar energy is utilized during the summer months to heat the water withdrawn from the aquifer. The heated water is then injected back into the aquifer. The stored warm water is withdrawn in winter to meet the heating needs of the building.

3.3. Coupling of ATES with a heat pump for both cooling and heating

Another alternative for ATES to meet the heating needs of buildings is its combination with a heat pump. Summer application of this alternative is same as the summer operation mode for the direct cooling alternative.

Warm water from aquifer acts as a low-temperature heat source for the heat pump (see Figure 3). Since, in this study (for the building located in Tehran), the heating energy needs are much smaller than the cooling needs, only a portion of the withdrawn water is needed to pass through the heat pump to provide the low-temperature heat source for it. The other part of the withdrawn water passes through the cooling tower. These two parts of withdrawn water are combined and then injected back into the aquifer for summer cooling.

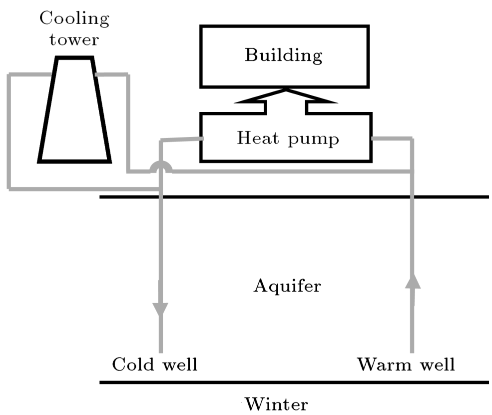

Figure 3. Combination of ATES with a heat pump for heating of the building (winter operation).

4. Modeling

4.1. Governing equations

Thermo-hydraulic analysis of the aquifer performance requires calculation of the groundwater flow and the temperature distribution in the aquifer and its surrounding layers. In this section, theoretical principles of water flow and heat transfer phenomena for calculating the temperature distribution inside the aquifer are explained. The coupled groundwater and heat flow are governed by the partial differential equations describing the mass and energy balances in the aquifer.

The aquifer is a porous medium. The continuity equation in a porous medium may be expressed by the following equation [21]:

$$\left[\frac{\partial(\rho\phi)}{\partial t} + \vec{\nabla}.(\rho\vec{q})\right] dV = S_f, \tag{1}$$

where S_f is related to source/sink term inside the porous medium and $\vec{q}$ is flow flux vector. It is obtained from the Darcy's equation:

$$\vec{q} = -K\vec{\nabla}h, \tag{2}$$

which is the governing equation for the flow in a porous medium. In this equation, K is the aquifer permeability.

The governing equation for heat transfer, including conduction and convection, is derived by applying the energy conservation principle in a porous medium [22]:

$$p_s\frac{\partial T}{\partial t} = \nabla^2(\lambda T) - (\rho c)_f\vec{q}.\vec{\nabla}T + S_H, \tag{3}$$

$$p_s = (\rho c)_f\phi + (\rho c)_S(1-\phi), \tag{4}$$

where, p_s, $(\rho c)_f$, and $(\rho c)_s$ are heat capacities per unit volume of aquifer, water, and the pebbles, respectively. Also, T, q, and S_H are temperature, flow flux, and energy source/sink terms inside the aquifer, respectively, while λ is a combined ratio that is a function of the thermal conductivity of water, pebbles, and aquifer porosity:

$$\lambda = \phi k_f + (1-\phi)k_s. \tag{5}$$

The main heat transfer phenomenon within the upper and lower surrounding layers of the aquifer is conduction. Therefore, we have:

$$\frac{\partial T}{\partial t} = \alpha\nabla^2 T. \tag{6}$$

4.2. Numerical modeling

In this research, the finite difference approach is employed for modeling of flow and temperature distribution in the confined aquifer under consideration, because of simple computational geometry and boundaries. Implementation and simulation in the finite difference method is simple. But, the quality of a finite difference approximation is often lower than that of the other corresponding approaches, such as finite element.

The computational domain is three-dimensional. Using finite difference approach is conventional in ATES flow and thermal modeling [21]. The flow and temperature equations are as follows:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = -\frac{S_f(x,y,z)}{K\rho dV}, \tag{7}$$

$$\begin{aligned}(\rho c)_s\frac{\partial T}{\partial t} =& \lambda\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] \\ &- (\rho c)_f\left[-K_f\left(\frac{\partial h}{\partial x}\vec{i} + \frac{\partial h}{\partial x}\vec{j} + \frac{\partial h}{\partial x}\vec{k}\right)\right] \\ &.\left(\frac{\partial T}{\partial x}\vec{i} + \frac{\partial T}{\partial x}\vec{j} + \frac{\partial T}{\partial x}\vec{k}\right) + S_H,\end{aligned} \tag{8}$$

$$\frac{\partial T}{\partial t} = \alpha\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right]. \tag{9}$$

The first step in the finite difference method is discretization. The numerical solution of the above equations is performed by using fractional steps in three dimensions [23]. Initially, the equation is solved using Crank-Nicolson implicit method, and results of the solution in one direction (for example, x direction) are used for solutions in other directions (y and z directions). In any direction, the solution is performed by applying the Thomas's TDMA[2] (Three Diagonal Matrix Algorithm) algorithm. Central difference scheme is used to discretize Eqs. (7), (8), and (9).

It should be noted that this method has second-order truncation errors in each direction. The advantage of this procedure is its unconditional stability and higher rate of convergence, because of using the TDMA method [23].

4.2.1. Meshing

The computational domain was cubic and three-dimensional. Since the boundary conditions in an aquifer are simple, using the uniform structured mesh is more applicable. Meshing was performed in such a way that injection/withdrawal wells were considered in all nodes of computational domain. Figure 4 shows the meshing arrangement.

For investigation of mesh size independency, so that a unique solution would be obtained, three series of mesh sizes were examined: $\Delta x = 0.5$ m, $\Delta y = 0.5$ m, $\Delta z = 0.25$ m with $\Delta t = 0.5$ hours; $\Delta x = 1$ m,

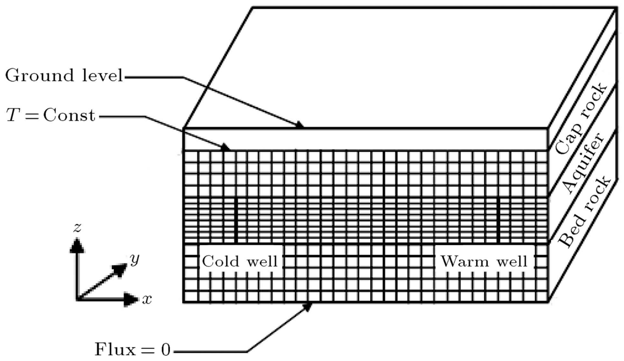

Figure 4. Three-dimensional computational domain.

$\Delta y = 1$ m, $\Delta z = 0.5$ m with $\Delta t = 1$ hours; and $\Delta x = 5$ m, $\Delta y = 5$ m, $\Delta z = 2.5$ m with $\Delta t = 10$ hours. The parameter on which the error was estimated was recovery factor of the aquifer (see Section 4.2.3). The time of simulation was 2 years for all of them. We found out that the recovery factor differences between the first and the second series and between the second and the third series were 1 and 5 percent, respectively, since the stability condition was fulfilled. Therefore, the second series was selected as interval steps.

4.2.2. Initial and boundary conditions

The boundary condition at the upper layer of cap rock is constant temperature. It is assumed that in its depth, the temperature remains constant throughout the year and it is approximately equal to the yearly average of the ambient air temperature of the location (Tehran). At the lower layer of the bed rock, the boundary condition is thermally insulated. The sides are also assumed to be thermally isolated. The initial temperature in the model domain linearly increases from the top to the bottom to express the thermal equilibrium state prior to thermal injection.

According to the condition, a value is considered for flow rates of the injection/withdrawal wells. This value is considered as the source term in Eq. (1). By considering groundwater velocity, a pressure gradient is added in the direction of x that is obtained from the Darcy equation. The initial head in the model domain is equal to the model elevation. Boundary condition on the lateral and the upper and lower sides is no flow.

4.2.3. Energy recovery factor in the aquifer

After determining the temperature field within the aquifer at different time steps, the amount of recovered energy from the aquifer is determined. The most important factor of ATES numerical modeling is the energy recovery factor. It indicates the amount of energy which can be recovered from the stored energy in the aquifer. Thermal energy recovery factor of an aquifer, η_A, is equal to the ratio of the extracted energy to the amount of injected energy, or:

$$\eta_A = \frac{Q_{\text{withdraw}}}{Q_{\text{injection}}}. \tag{10}$$

4.2.4. Coefficient of performance of the thermal energy storage system

In air conditioning systems (heating or cooling), the coefficient of performance is defined as:

$$\text{COP}_{\text{system}} = \frac{Q_{\text{required}}}{W}, \tag{11}$$

where Q_{Required} is the annual amount of energy requirement for cooling or heating of the building and W is the total annual electrical energy consumed to run the circulation pumps, cooling tower fans, chillers, and heat pumps.

5. Steps followed for the design of the ATES

To determine the parameters of an ATES, the following data must be available:

- Energy storage capacity;
- The maximum injection/withdraw rate and the temperature difference.

In the aquifer thermal energy storage system considered in this study, first, the amount of energy required for cooling or heating of the building complex is estimated. The aquifer parameters, such as thickness, porosity, and permeability, are generally obtained from the hydrological data available at the site. In general, the aquifer parameters vary in the domain. To simplify the investigation, constant values are assumed in this study [6]. Table 1 shows the aquifer properties employed in the analysis.

After determining the aquifer characteristics and the heating/cooling requirements of the building, the storage system can be designed as follows [24]:

1. Determine the specific heat capacity (p_s);

Table 1. Thermo-physical properties of the aquifer.

Property	Value
Aquifer permeability	0.0017 m/s
Porosity	0.3
Density of water	1000 kg/m^3
Density of pebbles	1800 kg/m^3
Specific heat of water	4200 J/kg K
Specific heat of pebbles	1292 J/kg K
Thermal conductivity of water	0.63 W/m K
Thermal conductivity of pebbles	1.3 W/m K

2. Determine the recovery factor of the aquifer, η_A. The recovery factor is calculated via numerical simulations. The aquifer dimensions and properties are supplied as inputs. First, an approximate value for the recovery factor of the aquifer is assumed. Then, at the end of the simulation procedure and after determining distance of the wells, the value of the recovery factor is calculated;
3. The required storage volume is calculated from the following equation:

$$V_{\text{storage}} = \frac{E_{\text{required}}}{p_S \Delta T \eta_A}. \quad (12)$$

   By dividing the storage volume to the injection/withdraw period, the amount of injection/withdrawal flow rate is obtained;
4. The horizontal area of the aquifer with the depth of b is determined from:

$$A = \frac{V_{\text{storage}}}{b}. \quad (13)$$

5. The distance between the wells is obtained from the following relation [24]:

$$R = \sqrt{A/1.05}. \quad (14)$$

6. With the known distance between wells and the injection/withdraw flow rate, the recovery factor of the aquifer is determined through the developed simulation code;
7. Steps 3 to 6 are repeated until the difference between the assumed and estimated values of the recovery factor of the aquifer is less than a certain amount.

6. Economic model

Economic investigation of energy systems can be conducted in two ways. One is the financial assessment that is used by buyers and only takes account of the capital and operational costs versus gained energy. Another method that has been used by governments and decision makers is called the economic assessment. In this method, all economic factors such as costs, taxes, and subsidies are generally considered. In the economic assessment, the following methods and factors are considered:

1. Life Cycle Cost (LCC) is the sum of all costs during application of the system based on the prices of the day;
2. Payback Period (PP) is the time required to recover all spent costs via incoming or saving money.

Economic evaluation based on the life cycle cost analysis is a perfect method for studying of commercial purposes.

6.1. The actual value of costs

In this method, not only the capital costs, but also the costs imposed during system operation are considered. The study period should be equal to the maximum lifetime of the elements of the considered system. After considering the capital investment and the operating and maintenance costs, it can be easy to detect the cheaper system by comparison. For a meaningful comparison, expenditures and revenues or costs and benefits should be expressed in the day worth of equivalent present value (PW) in the future. For this purpose, the discount or interest rate is used as follows:

$$PW = Pr \times FW, \quad (15)$$

where:

$$Pr = \frac{1}{(1+d)^n}, \quad (16)$$

where PW, Pr, d, and n are present worth, present worth factor, discount rate, and lifetime of the system, respectively. FW is the future worth of revenues or incomings. The annual interest or discount rate (d) is the depreciation percent of the invested capital in one year.

The economic calculation of the present values of the life cycle cost of expenditures or incoming includes two parts:

1. **Single payment:** The present worth of costs that are paid once in lifetime of the system (purchase, piping, and installation costs). The present value of a single payment can be obtained by replacing FW in Eq. (15):

$$PW = Pr \times Cr. \quad (17)$$

   Cr and Pr are the single payment cost and present worth factor, respectively. In this study, the piping and installation cost is assumed to be 5% of the total purchase cost;
2. **Annual payment:** The present worth of the expenditures that will be annually paid during lifetime of the system (operational and maintenance costs) and obtained as follows:

$$PW = Ca + Ca\left(\frac{1}{1+d}\right) + Ca\left(\frac{1}{1+d}\right)^2 + \cdots + Ca\left(\frac{1}{1+d}\right)^{n-1}. \quad (18)$$

   By allocation of $x = \frac{1}{1+d}$, Eq. (18) can be rewritten as:

$$\sum_{i=0}^{\infty} x^i = 1 + x + x^2 + \cdots = \frac{1}{1-x}, \quad (19)$$

$$Pa = 1 + x + x^2 + \cdots + x^n = \frac{1}{1-x} - \sum_{i=n}^{\infty} x^i$$

$$= \frac{1}{1-x} - x^n \sum_{i=0}^{\infty} x^i = \frac{1-x^n}{1-x}. \quad (20)$$

Eq. (18) can be briefly rewritten as follows:

$$PW = Pa \times Ca, \quad (21)$$

where:

$$Pa = \frac{(1+d)^n - 1}{d(1+d)^{n-1}}. \quad (22)$$

Ca and Pa are the annual cost and the cumulative present worth factor, respectively. When the discount rate is smaller, the present worth factor is larger and by reduction of the discount rate, the costs that should be paid in the future gain higher actual worth [25]. The maintenance cost is usually considered as a portion of the purchase cost. In this study, this cost is assumed to be 2% of the capital investment at the first operational year.

6.2. Life Cycle Cost (LCC)

By using the present worth factor of Pr and Pa for all types of costs, the present worth can be calculated. The summation of all of the present worth is equal to the total cost that will be paid during lifetime of the system and is called LCC:

$$\text{LCC} = \sum_i PW_i. \quad (23)$$

By having and comparing the LCCs of different systems, the suitable system can be selected economically [25].

6.3. Annualized Life Cycle Cost (ALCC)

This quantity is obtained by dividing LCC to the cumulative present worth factor and its unit is the currency per year:

$$\text{ALCC} = \frac{\text{LCC}}{Pa}. \quad (24)$$

6.4. Payback period

This study is a comparative study; thus, the payback period is important in it. First, the energy production cost is calculated for the basic case based on the LCC method. This cost is our criterion for comparison. For determination of payback period, the expenditures for energy production in different systems and alternatives should be compared with each other. The relations for calculation of payback period are as follows:

$$PW_c = PW_b, \quad (25)$$

PW_c is the present worth of the total cost (single and annual costs) and PW_b is the present worth of the incomings (cost of energy production in basic case). Then, we have:

$$\text{LCC} = E \times P \times \left[\frac{(1+d)^n - 1}{d(1+d)^{n-1}}\right], \quad (26)$$

where n, d, E, and P are payback period, discount rate, annual energy production (energy requirement), and cost of energy production unit (basic case), respectively.

7. Discussion of the results

7.1. Numerical model verification

The important parameter in ATES system that has a key role on the performance of the system is the withdrawal temperature. A verification was performed by using the FLUENT software and simulation of computational domain. The computational domain is shown in Figure 5. In this meshing, an unstructured 3D mesh of 259346 cells was built. The chosen element was Tet/Hybrid and its type was TGrid. For validation of the cold and warm wells, temperatures were compared with the ones which had been obtained via the developed code (Table 2) during two years. The results show a good agreement between the developed code and the ones that were obtained using FLUENT.

7.2. Design of the ATES system for cooling and heating of the building

The input parameters are listed in Table 3. Design simulation is carried out as explained in Section 5. The results of the design simulation are listed in Table 4.

For cooling and heating of the building complex, we have coupled the ATES system with a heat pump. Since the annual cooling needs in TJ/year are much higher than the annual heating needs, we base our design on the annual cooling requirements. For this reason, when solar collectors are coupled with ATES for thermal energy storage for heating of the building complex, a much smaller aquifer would be needed.

The estimated pressure losses in the system are listed in Table 5. These values were determined

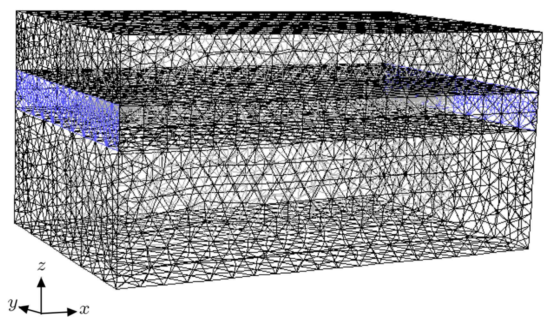

Figure 5. Model mesh in FLUENT.

Table 2. Model verification with results of FLUENT simulation.

t (day)	Warm well temperature			Cold well temperature		
	T_{FLUENT} (°C)	T_{Code} (°C)	Error (%)	T_{FLUENT} (°C)	T_{Code} (°C)	Error (%)
90	12	12	0	3	3	0
180	12	12	0	3	3.13	4.15
270	14	14	0	8.64	8.94	3.35
360	13.31	13.86	3.96	10.2	10.66	4.31
450	12.35	12.8	3.51	3	3	0
540	11.89	12.34	3.64	3.48	3.58	2.79
630	14	14	0	8.59	8.82	2.6
720	14	13.86	1.01	10.34	10.53	1.8

Table 3. Input information for the design of the ATES system.

Quantity	Cooling and a heat pump coupled with ATES for heating	Flat-plate solar collectors coupled with ATES for heating
Injection temperature in winter (°C)	3	43
Injection temperature in summer (°C)	14	65
Initial recovery factor of the aquifer (%)	70	70
Aquifer height (m)	16	16
Cap rock height (m)	25	25
Bed rock height (m)	50	50
Groundwater velocity (m/year)	5	5
Groundwater temperature (°C)	12	12
Aquifer initial temperature (°C)	12	12
The temperature of upper surface of the cap rock layer (°C)	18	18
The energy that should be stored (TJ/y)	8.7 (cooling requirements)	1.9 (heating requirements)

Table 4. Results of the different operational alternative designing.

Quantity	Cooling and a heat pump coupled with ATES for heating	Flat-plate solar collectors coupled with ATES for heating
The recovery factor of the aquifer (%)	73	63
Aquifer length (m)	182	80
Aquifer width (m)	116	32
Injection/withdraw rate L/s	32.5	7.5
Aquifer volume (m^3)	337080	35387
The area of the horizontal surface of the aquifer (m^3)	21067	2527
Distance of the wells (m)	142	50
Coordination of cold well in horizontal surface of the aquifer	$x = 20$ m $y = 58$ m	$x = 15$ m $y = 16$ m
Coordination of warm well in horizontal surface of the aquifer	$x = 162$ m $y = 58$ m	$x = 65$ m $y = 16$ m

Table 5. Pressure losses for different sections of the ATES system.

Unit	Direct cooling	ATES coupled with heat pump	ATES coupled with solar collectors
$\Delta P_{\text{friction loss}}$ (m)	51.12	51.12	26.68
ΔP_{depth} (m)	45	45	40
$\Delta P_{\text{well pairs}}$ (m)	1.19	1.19	0.1
$\Delta P_{\text{fitting}}$ (m)	5	5	0.5
$\Delta P_{\text{heat exchanger}}$ (m)	2.25	2.25	1.2
$\Delta P_{\text{heat pump}}$ (m)	—	1.5	—
$\Delta P_{\text{cooling towers}}$ (m)	16	16	—
$\Delta P_{\text{solar collectors}}$ (m)	—	—	8
ΔP_{total} (m)	120.56	122.06	78.48

supposing 250 m of straight pipes, 10 elbows, a pipe diameter of 10 cm for the alternatives of direct cooling and the coupled ATES with heat pump and 5 cm of pipe for the coupled ATES with solar collectors, 2.5 cm of diameter for tube in the shell and tube heat exchanger with 5 m of length, and finally 45 m of depth for the wells. The head needed for the cooling tower pumps, and the pressure losses through the heat pump and the solar collectors were obtained from the manufacturers' catalogues [26-28]. The pressure losses due to friction were calculated from the Moody's diagram by considering the Reynolds number and roughness of the pipe that was supposed to be commercial steel.

7.3. Economical assessment

Table 6 shows the specifications and costs of the equipment that have been used in different alternatives and in the basic case [26-32]. For economic analysis and comparison of energy systems, the annualized capital cost, fuel cost, and maintenance cost should be calculated. The discount rate and lifetime of all of the systems have assumed to be 20% and 20 years, respectively. The electricity and natural prices are local prices in Iran that are considered to be 0.032 \$/kWh and 0.04 \$/m^3, respectively.

The electricity and natural gas consumption in each of the abovementioned alternatives are obtained by using Ret Screen software. These values are obtained by this assumption such that all of these alternatives can satisfy heating and cooling requirements. In Figure 6, the electricity and natural gas consumption of the different alternatives and basic case are compared. In the alternatives of coupled ATES with heat pump and coupled ATES with solar collector, natural gas is not consumed and the heating of the building is satisfied through a new system. In the basic case and the alternative of direct cooling, the heating requirement is supplied via gas fired boiler and, therefore, these systems have the same natural gas consumption. The highest electricity consumption is of compression chiller and, then, the consumption of the basic case and coupled ATES with solar collector is higher than that of other systems. In the direct cooling alternative, electricity consumption is less than other alternatives; this is also the case for the pump consumption.

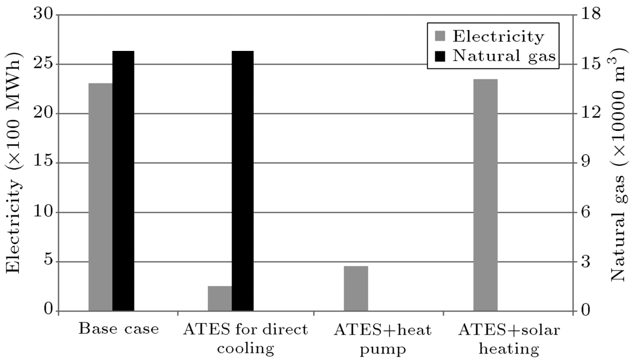

Figure 6. Comparison of energy consumption of different alternatives.

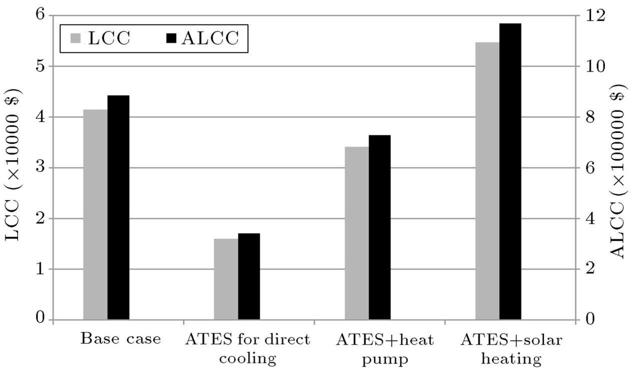

Figure 7. Comparison of LCCs and ALCCs of different alternatives.

In Figure 7, the values of LCC and ALCC are provided for different alternatives. The highest values are of the coupled ATES with solar collectors and the basic case, respectively. As seen in Table 6, the highest capital investment is of compression chiller that is used

Table 6. Specifications of the equipment for different alternatives.

Equipment	Specifications	Number	Manufacturer	Cost ($)
		Basic case		
Cooling				
Compression chiller	Capacity: 160 TR Type: Screw	2	Sarma Afarin-Iran [29]	228000
Heating				
Boiler	Capacity: 600 kW Type: Water tube	1	Tahvieh Damavand-Iran [30]	12000
		ATES for direct cooling		
Cooling				
Pump	Head:120 m Flow: 32.5 L/s Power: 36 kW	2	Pumpiran-Iran [31]	9200
Heat exchanger	Type: shell & tube Heat rate: 1000000 kcal/hr Flow: 515 gpm	1	Tehran Mobaddel-Iran [32]	29400
Cooling tower	Flow: 515 gpm	1	Damatajhiz-Iran [27]	3800
Pipe	Steel	300 m	Iran	2400
Wells drilling	—	120 m	Iran	4800
Feasibility study	—	—	Iran	8000
Ground preparing	—	—	Iran	4000
Hydrology tests	—	—	Iran	4000
Justifications	—	—	Iran	20000
Heating				
Boiler	Capacity: 600 kW Type: water tube	1	Tahvieh Damavand-Iran [30]	12000
		Coupled ATES with heat pump		
Cooling				
Pump	Head: 120 m Flow: 32.5 L/s Power: 36kW	2	Pumpiran-Iran [31]	9200
Heat exchanger	Type: shell & tube Heat rate: 1000000 kcal/hr Flow: 515 gpm	1	Tehran Mobaddel-Iran [30]	29400
Cooling tower	Flow: 515 gpm	1	Damatajhiz-Iran [27]	3060
Pipe	steel	300 m	Iran	2400
Wells drilling	—	120 m	Iran	4800
Feasibility study	—	—	Iran	8000
Ground preparing	—	—	Iran	4000
Hydrology tests	—	—	Iran	4000
Justifications	—	—	Iran	20000
Heating				
Heat pump	Capacity: 600 kW Type: water to water	30	Miami Heat Pump-USA [28]	128000

Table 6. Specifications of the equipment for different alternatives (countinued).

Equipment	Specifications	Number	Manufacturer	Cost ($)
	Coupled ATES with solar collector			
Cooling				
Compression chiller	Capacity: 160 TR Type: Screw	2	Sarma Afarin-Iran [29]	228000
Heating				
Pump	Head: 75 m Flow: 7.5 L/s Power: 13 kW	2	Pumpiran-Iran [31]	4000
Heat exchanger	Type: shell & tube Heat rate: 300000 kcal/hr Flow: 100 gpm	1	Tehran Mobaddel-Iran [32]	11400
Solar collector	Type: Glazed	450	Watt-Poland [26]	40000
Pipe	Steel	300 m	Iran	1800
Wells drilling	—	120 m	Iran	4800
Feasibility study	—	—	Iran	8000
Ground preparing	—	—	Iran	4000
Hydrology tests	—	—	Iran	4000
Justifications	—	—	Iran	20000

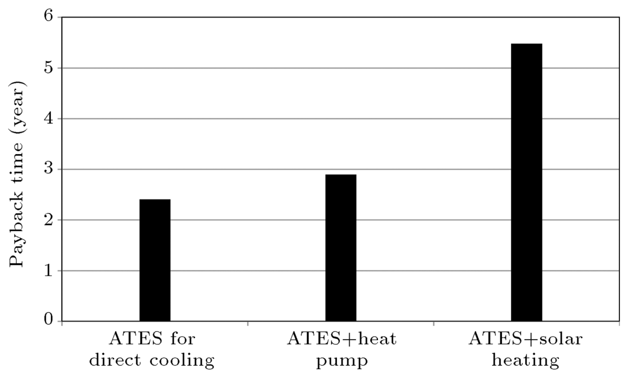

Figure 8. Payback time of different alternatives.

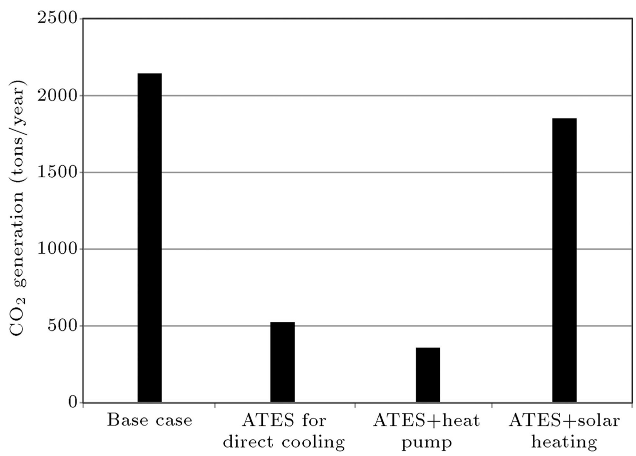

Figure 9. Comparison of CO_2 emission of different alternatives.

in these alternatives and has a greater portion in their LCC and ALCC. Moreover, the electricity consumption of these alternatives is too much that leads to high LCC and ALCC. The alternative of the direct cooling has the minimum LCC and ALCC because of its low capital investment.

Figure 8 shows the payback period of three investigated alternatives. Because of low capital investment and low operational cost of the alternative of the direct cooling, this alternative has the minimum payback period.

7.4. Environmental assessment

The main index of environmental sustainability of an energy system is the amount of CO_2 emission. CO_2 emission of different alternatives is shown in Figure 9.

The alternative of the coupled ATES with heat pump has low electricity consumption and zero natural gas consumption. Therefore, its CO_2 emission is less than other alternatives. Also, the basic case has the maximum CO_2 generation because of much electricity and natural gas consumption.

8. Conclusion

In this study, 3 different operational alternatives of ATES (using ATES for direct cooling, coupling of ATES with heat pump for both cooling and heating, and coupling of ATES with flat-plate solar collectors for heating) were economically and environmentally compared with each other and with the basic case. These systems were employed to store the thermal energy needs of a residential complex, located in Tehran, Iran. The objective was the storage of 8.7 TJ and 1.9 TJ of energy for summer cooling and winter heating, respectively. The LCC method and the Ret Screen version 4.0 software were used for economic and environmental assessment. The important concluding remarks of this research are the following:

- The highest fuel (electricity and natural gas) cost was for the basic case that was used as boiler and compression chiller for heating and cooling, respectively;
- The alternative of coupled ATES with solar collector and basic case had maximum and the alternative of ATES for cooling alone had minimum LCC;
- The payback periods of the alternatives of ATES for cooling alone, coupled ATES with heat pump for cooling and heating, and coupled ATES with flat-plate solar collectors were 2.41, 2.9, and 5.48, respectively;
- The alternative of coupled ATES with heat pump for heating and cooling had the minimum CO_2 emission (359.32 tones/year).

Nomenclature

A	Area, cross section (m^2)
ALCC	Annualized Life Cycle Cost ($)
b	Aquifer thickness (m)
c	Specific heat (J/kgK)
Ca	Annual cost ($)
Cr	Single payment cost ($)
COP	Coefficient Of Performance
d	Discount rate (%)
E	Energy (J)
FW	Future value ($)
g	Gravitational acceleration (m/s^2)
h	Hydraulic head (m)
K	Permeability (m/s)
k	Specific permeability (m^2)
L	Length (m)
LCC	Life Cycle Cost ($)
n	Life time, payback (year)
p	Specific heat capacity (J/m^3K)
P	Price of energy production unit ($/J)
Pa	Cumulative present factor
Pr	Present worth factor
PW	Present value ($)
q	Specific velocity (m/s)
Q	Heat (J)
R	Wells distance (m)
S	Flow source term (kg/s) and heat source term (J/m^3K)
t	Time (s)
T	Temperature (K)
V	Volume (m^3)
$\dot{V}$	Flow rate (m^3/s)

Greek Symbols

α	Diffusivity (m^2/s)
η	Efficiency
ϕ	Porosity
λ	Aquifer thermal conductivity (W/m/K)
ρ	Density (kg/m^3)

Subscripts

A	Aquifer
f	Fluid
gw	Groundwater
imp	Imposed
injection	Injection
O	Overall
Rock	Rock or pebbles
S	Specific, solid
V	Void
water	Water
withdraw	Withdraw

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