323: Climate-robust design of zero energy buildings with aquifer energy storage

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Abstract

This paper presents the effects of global warming and a changing climate on zero energy buildings using aquifer thermal energy storage. Aquifer thermal energy storage is an effective way to reduce the energy consumption and to work towards a zero energy building. However, aquifer thermal energy storage systems depend on the resulting thermal energy balance in the aquifer. This energy balance is strongly affected by the characteristics of the outdoor climate. This paper addresses the effects of global warming scenarios on aquifer systems in the Netherlands. Four scenarios for the climate change as developed by the KNMI have been applied. Subsequently, the heating and cooling demand of a typical office building are evaluated as well as the dimensions of the dry cooler system that is used to obtain a zero energy balance in the aquifer. For the 2030s a decrease of 25 - 29% is possible for the heating demand, while the corresponding increase of the cooling demand is in the range of 21 - 36%. It has been shown that the power of the dry cooler system can vary a factor 3.6 to obtain a zero energy balance in the aquifer. A more climate-robust design can be obtained by a strong reduction of the internal heat gains due to office equipment and lighting.

Keywords: zero energy buildings, aquifer energy storage, climate change.

1. Introduction

Zero energy buildings are often designed using one set of data for the outdoor climate conditions. Building service engineers use a single year for modelling the energy demand of buildings, a so-called design reference year. These design reference years consist of climate data of 12 months which represent the average current climate conditions. However, the energy demand of buildings will change due to a changing outdoor climate. There is a large consensus that due to the effects of global warming a significant change of the outdoor climate can be expected. This will lead to a changing energy demand for the heating and cooling of buildings. Also the quality of the indoor climate will change, due to the more extreme conditions during the summer period. For the UK and Switzerland, future climate scenarios have been evaluated quite recently [1,2,3]. Jenkins et al. investigated the impact of a climate change scenario for the 2030s in the UK [1]. With an ambient temperature increase of 0.8 – 1.0 °C, they found a decrease in the space heating demand of 9 – 12%, and an increase of the cooling demand in the range of 30 – 42%. As indicated, in [1], the results are also strongly related to the internal heat gains due to office applications and lighting. Holmes et al. performed computations for a period until the 2080s in the UK. Their focus was the impact of climate change on overheating effects, related to the ventilation strategy. They reported a decrease of the space heating demand up to 37% in the 2080s, related to the year 1989. They applied a climate scenario which gives a global temperature increase of about 2.3 K in the 2080s. Frank reports a 33–44% decrease in the annual heating energy demand for Swiss residential buildings for the period 2050–2100. For the time horizon 2050–2100, he used a climatic warm reference year scenario that foresees a 4.4 °C rise in mean annual air temperature relative to the 1961–1990 period [3].

The mentioned papers on the impact of climate change on buildings have their focus on the demand side of building energy. Jenkins et al. also pay attention to the supply side. They incorporate the effect of the climate change on the boiler efficiency as well as the coefficient of performance of conventional chiller units. For an integral design approach of zero energy buildings it is also important to investigate renewable energy supply sources in this context.

This paper presents the effects of global warming and a changing climate on buildings using aquifer thermal energy storage. In ATES (Aquifer

Thermal Energy Storage) systems groundwater is used to carry the thermal energy into and out of an aquifer. During summer operation, cold water from the cold well can be used for cooling applications. During winter operation the hot well provides heat at a low temperature level as a source for a heat pump (see also Figure 7). ATES is an effective way to reduce the energy consumption for heating and cooling of buildings. It is an option to use electrical heat pumps in combination with solar power and/or wind energy to work towards a zero energy building. Figure 1 gives the results of three design configurations for a (Dutch) office building. The leftmost one represents a typical Dutch office building with averaged characteristics for the insulation, lighting and office equipment [8]. The second one shows the impact of a strong reduction of the energy consumption of printers, copiers and computers (office equipment interventions). The building characteristics are discussed in the next sections. The third configuration shows the effect of using a heat pump and aquifer instead of a conventional boiler and chiller. It is shown that the heat pumps and aquifer storage give a reduction of the energy needed for heating and cooling of about 48%. In order to fully achieve a zero energy building, the lighting and the ventilator energy need further attention. The residual electricity demand of the building with equipment intervention and ATES is still 49 kWh per m^2 gross floor area. Using photovoltaic cells, this would require about 0.5 m^2 PV per m^2 gross floor area for a zero energy building.

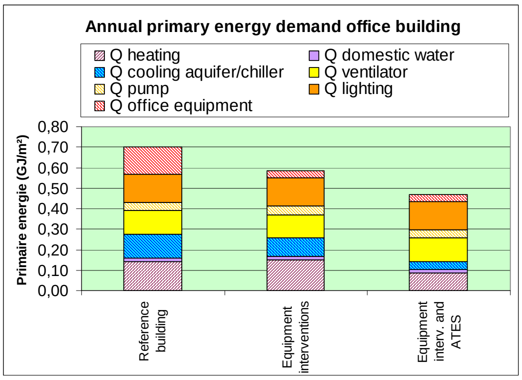

Figure 1 Energy consumption due to ATES with respect to the gross floor area. Current climate conditions.

The impact of the aquifer energy storage is significant. However, aquifer thermal energy storage systems strongly depend on the resulting thermal energy balance in the aquifer. A zero energy balance in the aquifer over a number of years is necessary to prevent a short-circuit between the hot and the cold well. It is obvious that the energy balance in the aquifer is determined by the ratio between the cooling demand and the heating demand of the building. Apart from human behaviour, the use of office appliances, lighting, et cetera, the variation in the outdoor climate strongly influences this ratio.

2. Scenarios for a changing climate

2.1 Reference years

The design reference years form the point of departure for the scenarios for climate change. Before applying climate change scenarios we investigate which design reference year best represents the current climate conditions. In this paper we focus on the Dutch climate. For a number of years, the data of April 27th 1964 until April 27th 1965 were used as a design reference year for the Netherlands. In 2006, the new design reference year Tempref was presented by Isso [4]. We compared the data of both design reference years to the data from the period 1976-2005. The data from this period represent the average climate conditions around the year 1990 and have been used by the KNMI as a point of departure for their climate change scenarios [5].
Figure 2 gives a comparison of the average monthly temperatures for the data of 1964/1965, Tempref and the KNMI data between 1976 and 2005. The data of Tempref agree best with the KNMI data between 1976 and 2005. We used Tempref to construct new design reference years based on the KNMI Scenarios.

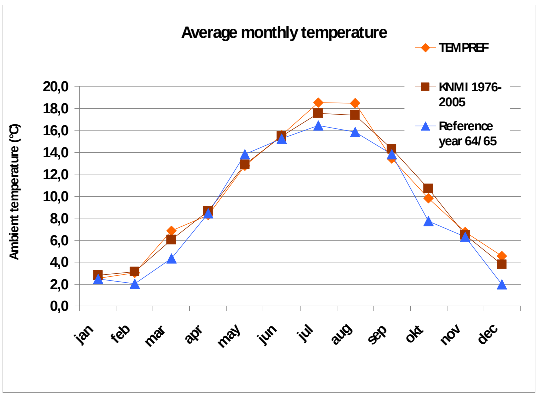

Figure 2 Average monthly temperatures for design reference years and weather data between 1976 – 2005. Location: de Bilt, Netherlands.

2.2 KNMI Climate Change scenarios

Using global climate models, regional climate models and Dutch historic measurement series, the KNMI developed four scenarios [5]:

- G and G+
- W and W+

The G scenarios correspond with a global temperature rise of 1°C in 2050 with respect to 1990, while the W scenarios correspond to a global temperature rise of 2°C in 2050 with respect to 1990. In the '+' scenarios, a change occurs in the global air circulation above Europe.

2.3 Scenario design reference years

Following the G(+) and W(+) scenarios, we derived four scenario design reference years. This was done in the following way:

- Using the KNMI interpolation method to incorporate monthly changes as described in [7], as well as the KNMI scenarios [5], time series of hourly temperatures were derived for the period 2016 – 2045. This period represents the climate for the 2030s.
- The data for the design reference years were selected from these scenario data, from the period 2034-2043. The selection method was similar to the selection of the original Tempref months. The original Tempref consists of series of measured weather data. Following ISO 15927-4, each month corresponds to one of the months of the reference period [6]. For Tempref, the reference period is 1994 – 2003. In the original Tempref, the January data correspond to the January data of 2003. For the transformed Tempref, the January data were taken from the scenario data of the year 2043. This procedure has been applied for every month of the year.

Figure 3 gives the results of the average monthly temperatures for the scenario design reference years, as well as the data of Tempref.

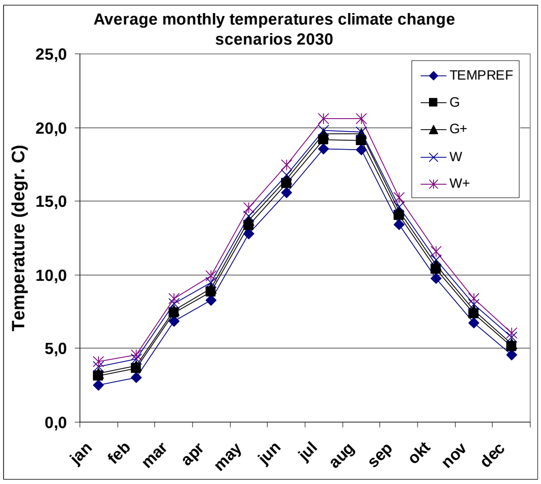

Figure 3 Climate scenarios for the Netherlands in the 2030s.

3. The changing energy demand of buildings

3.1 Computational method

The impact of the climate change has been analysed for a typical office building in the Netherlands. The building characteristics will be discussed in the next subsection. Here, we briefly summarize the computational method used to calculate the energy demand of the office. The hourly weather data of the scenario design reference years have been transformed into a frequency table with integer numbers of the ambient temperature and the frequency with which this temperature occurs. For each integer number of the ambient temperature, the heating and/or cooling power has been computed, including the effects of ventilation, insulation levels, internal and external heat gains and the required temperature levels in the building. For further details we refer to Isso 81 [8]. Due to the frequency approach, the dynamic behaviour of the thermal mass is not incorporated. Therefore, the model is limited to energy flow computations. Overheating effects and peak requirements for heating and cooling cannot be predicted.

3.2 Building characteristics

The building characteristics are given in Table 1. The entire energy consumption is also strongly influenced by the power for office equipment and lighting. This is strongly user dependent. Therefore, we analysed two user characteristics for the office equipment. The first one represents a reference building with average power characteristics for a Dutch office building [8]. The second one corresponds to an office building with low energy computers, printers, copiers, etcetera (office equipment intervention). The power characteristics correspond to the lowest boundary of the band width of a Dutch office building [8]. The computational values are given in Table 2.

Table 1 Summary Building characteristics

Characteristic	symbol	Value
Gross floor area	M2	20.000
Room height	M	3
Glazing percentage building façade	%	50
Ventilation system	-	Mechanical, supply and return, including heat recovery
Efficiency heat recovery ventilation	%	75
Air change rate	Ac/h	2
Heating and cooling supply		Conditioning of the ventilation and local heating and cooling in the rooms
Insulation values construction	m2.K/W	3
U-value glazing	W/m2.K	1.7

Table 2 Characteristics office equipment and lighting

Characteristic	symbol	Value
Installed power for lighting	W/m2	11
Utility factor for lighting	-	1
Installed power reference building		20
Utility factor for office equipment reference building		0,4
Installed power building with equipment interventions		10
Utility factor for office equipment building with equipment interventions		0,2
Operational time	H/year	2610

3.3 Results for the energy demand

The entire yearly primary energy consumption of the two buildings is given in Figure 1. The heat is supplied by a conventional boiler (efficiency 85%), while the cold is generated by a conventional chiller (Coefficient of performance = 3.0). For the building with equipment interventions, the energy consumption is also given for heat and cold supply using a heat pump and aquifer thermal energy storage. For the heat pump we applied a computational value for the COP equal to 4, while the value of the COP for the cold supply of the aquifer was equal to 17. These values have been observed in an extensive monitoring program of office building 'de Thermo-Staete' in the Netherlands [9]. For the design cases of this study, the heat pump and the aquifer were used for the base load of the heat and cold supply. Peak requirements were delivered by a boiler and the heat pump acting as a chiller. For the heating, 90% of the heating energy is supplied by the heat pump, while for the cooling energy 73% is supplied by the aquifer.

The results in Figure 1 are derived for the heat and cold demand given the climate data of Tempref.
Figure 4 and Figure 5 show the heating and cooling requirements for the different (scenario) design reference years as well as for Tempref and the climate data of 1964/1965. Figure 6 shows the energy consumption of the design configurations for the climate conditions of W+.

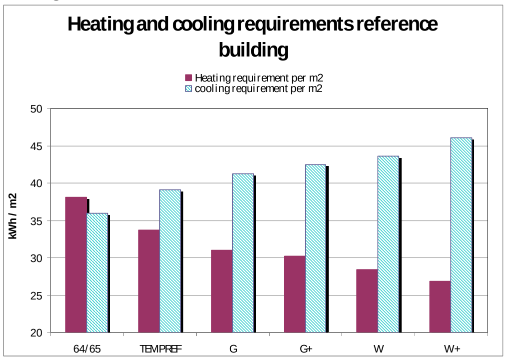

Figure 4 Heating and cooling requirements with respect to the gross floor area. Reference building.

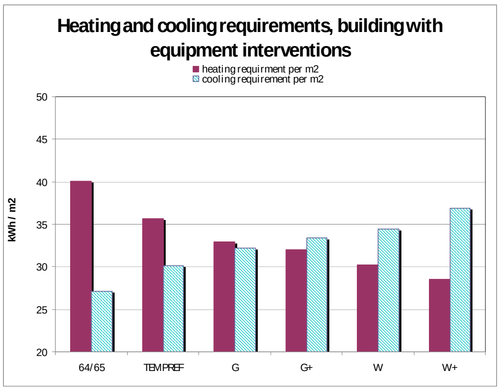

Figure 5 Heating and cooling requirements with respect to the gross floor area. Building with equipment intervention.

The change of the entire energy consumption is relatively small, compared to the results of Figure 1. The reduction for the required primary energy for heating and cooling due to application of the heat pump and aquifer storage is 47%. However, due to the changing energy requirements for heating and cooling, the energy balance in the aquifer will differ significantly.

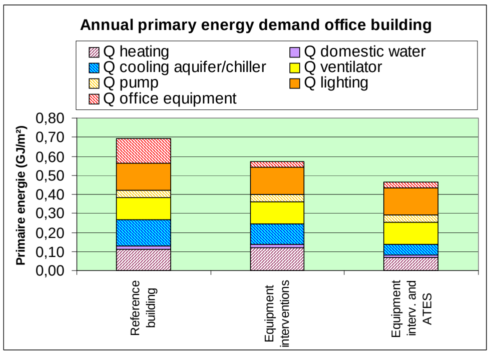

Figure 6 Energy consumption due to ATES with respect to the gross floor area. Climate conditions: W+.

4. Zero energy balance of the aquifer

Strong deviations from a zero energy balance will lead to a short circuit between the hot well and the cold well of the aquifer. Furthermore, due to Dutch legislation requirements, the maximum allowed deviation from a zero energy balance is 0 to 5%. This maximum boundary of unbalance depends on the Province where the aquifer is located. For this paper we assume a zero tolerance for the deviation from a zero energy balance.
The energy balance in the aquifer is determined by the following energy flows (see Figure 7):
1. During winter operation, the heat pump supplies cold to the cold well. The energy flow is determined by the heat requirements of the building and the COP of the heat pump.
2. During summer operation, the cold well supplies cooling energy to the building.

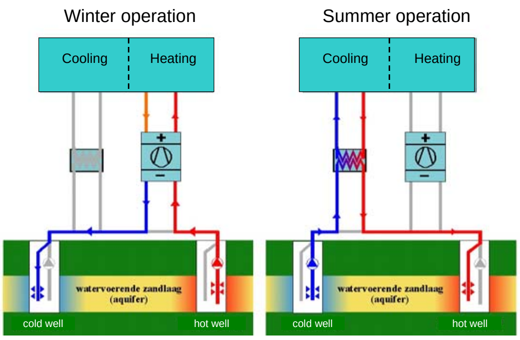

Figure 7 Energy flows aquifer due to heating and cooling. No application of additional measures to obtain a zero energy balance.

When no additional measures are applied, a zero energy balance will be a matter of an accidental coincidence. In many office building applications, additional cooling energy is added to the cold well during winter using dry coolers. For the reference building we obtain the energy balance for the Tempref scenario as given in Table 3. In the W+ scenario, the energy demand for cooling of the building will increase, while the cooling energy production by the heat pump decreases, due to the decreasing heating energy demand of the building. Therefore, the required energy production of the dry coolers increases with a factor 2.2 (see Table 4).

Due to the increasing outdoor temperature, also during winter, the required size of the dry cooler will increase with a factor larger than this factor 2.2. Related to Tempref, the required power of the dry cooler is a factor 3.6 larger for the W+ scenario. The size of the dry coolers depends also on the minimum value of the part-load of the dry coolers as shown by Figure 8. However, using a lower values for the minimum part-load ratios will affect the COP of the dry coolers. This effect is shown in Figure 9. The COP has been computed for each integer value of the ambient temperature. The delivered cooling power of the dry cooler follows from:

- the ambient temperature
- the temperature difference over the heat exchangers and the temperature efficiency of the dry cooler
- the temperature difference between the hot and the cold well
- the flow rate of the aquifer system

Together with the required fan power and the pump energy, the COP has been computed. Using time series of the ambient temperature, the yearly average COP was derived.

Including the effect of the dry coolers, the COP of the aquifer is 15.5 for the Tempref conditions instead of the mentioned 17, which is valid without incorporation of the effect of the dry coolers. For the W+ conditions, the overall COP of the aquifer and the dry cooler equals 14.1.

For the building with office equipment interventions, the energy balance is less critical. Figure 10 gives the required power of the dry cooler for cooling energy supply to the cold well. In case of a climate represented by the data of 1964/1965, Tempref and the G scenario, heating energy has to be supplied to the hot well. This can be done using the heat production of the condensor of the heat pump during cooling supply to the building.

Table 3 Energy balance in the aquifer for the reference building. Climate data: Tempref.

Characteristic	symbol	Cooling energy supplied by the cold well	Cooling energy supplied to the cold well
Cooling energy flow	kWh	576.472	462.583
Dry cooler	kWh	0	113.889
Total energy flow	kWh	576.472	576.472

Table 4 Energy balance in the aquifer for the reference building. Climate data: W+

Characteristic	symbol	Cooling energy supplied by the cold well	Cooling energy supplied to the cold well
Cooling energy flow	KWh	625.393	374.823
Dry cooler	KWh	0	250.570
Total energy flow	KWh	625.393	625.393

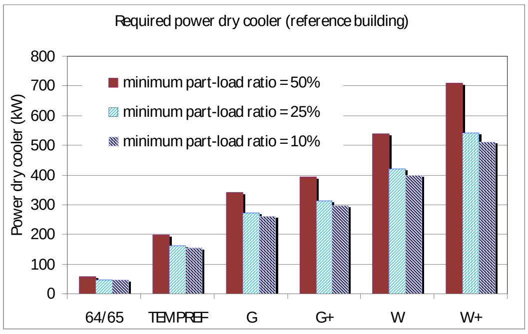

Figure 8 Required power for the dry cooler (reference building with ATES).

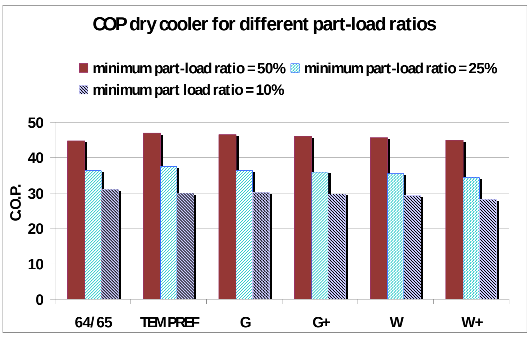

Figure 9 Yearly average COP dry coolers (reference building with ATES).

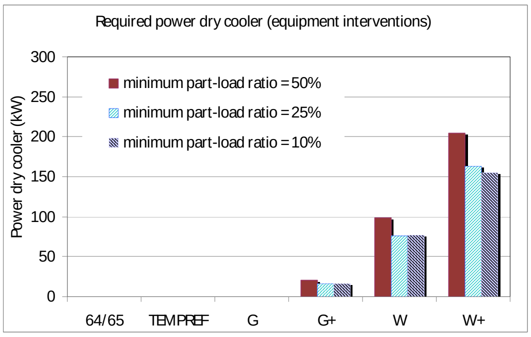

Figure 10 Required power for the dry cooler (building with equipment interventions and ATES).

The changing dimensions of the required dry coolers strongly affect the investment costs for the aquifer system. Figure 11 shows the investment costs for the main components of the aquifer system for the reference building. In the W+ scenario the costs of the dry coolers exceed the costs of the heat pump.

The cost estimations are valid for the Netherlands and are based on the following assumptions:
- Aquifer maximum flow rate = 107 m^3/h
- The power of the heat pump equals 210 kW

The investment levels are based on consultancy experience of the authors. For the current computations we used the following numbers:
- Dry coolers: 140 Euro/kW
- Aquifer wells: 2500 Euro/m^3/h
- Heat pump: 325 Euro/kW

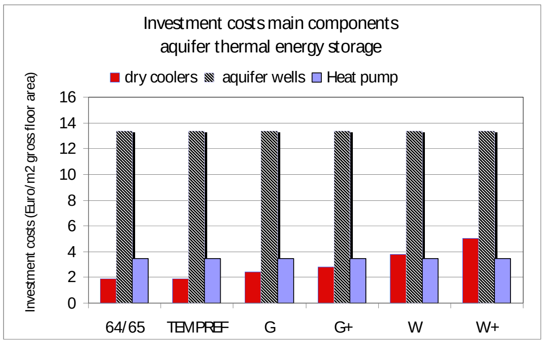

Figure 11 Investment costs main components aquifer system with respect to the gross floor area of the building.

5. Conclusions

Climate change strongly affects the ratio between the heating and cooling requirements of typical office buildings in the Netherlands.
For the 2030s a decrease of 25 - 29% is possible for the heating demand, while the corresponding increase of the cooling demand is in the range of 21 - 36% (with respect to the design reference year 1964/1965). For the design of zero energy buildings this is an important feature.

Applying aquifer energy storage is an important strategy towards a zero energy building. The reduction of the energy for heating and cooling is about 48% with respect to a conventional heating and cooling system with a conventional boiler and chiller.

It has been found that the influence of the climate change on the entire energy consumption of the building is relatively small. This is due to the summing up of the decreasing heating energy and the increasing cooling energy.

For the design of aquifer systems the implications are more far-reaching. The measures for a zero energy balance in the aquifer itself need adaptation. In case of the reference office building, the required power of the dry coolers varies a factor 3.6. For the most extreme climate scenario investment costs of the dry coolers will exceed the investment level of the heat pumps.

The building with office equipment intervention gives a much more climate-robust design. As long as the heating requirements exceeds the cooling requirements it is more straightforward to obtain a zero energy balance in the aquifer. Using an integral design approach for a zero energy building, reduction of the energy demand of the office and the lighting equipment are essential. The resulting reductions of the internal heat gains give a more climate-robust design of aquifer systems as an important spin-off.

6. References

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