Applied Energy 228 (2018) 1499–1505

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Relating groundwater heat-potential to city-scale heat-demand: A theoretical consideration for urban groundwater resource management

Jannis Epting[a,*], Matthias H. Müller[a], Dieter Genske[b], Peter Huggenberger[a]

[a] Department of Environmental Sciences, Applied and Environmental Geology, University of Basel, Switzerland
[b] Hochschule Nordhausen, Germany

HIGHLIGHTS

- Thermal 'waste energy' - Exploitation of the heat-potential of urban subsurface resources.
- Quantitative methods as the scientific basis for thermal management strategies.
- Index relating groundwater heat-potential to heat-demand.
- Evaluating the spatial distribution of heat-potential to heat-demand.
- Temporal evolution of the heat-potential for selected urban.

ARTICLE INFO

Keywords:
Waste heat recovery
Heat-potential
Heat-demand
Thermal management
Flow- and heat transport modeling
Specific advective heat fluxes

ABSTRACT

To sustainably plan the use of subsurface resources, a discussion about thermal management is needed, as well as a more coordinated and efficient thermal use of subsurface resources.

This contribution outlines a theoretical consideration for how to effectively manage urban subsurface resources. The consideration is made by means of assessing the heat-potential from urban groundwater resources against the background of heat-demand. We illustrate that, in principle, the heat-potential of subsurface resources could be directly 'mined' to exploit them and store thermal 'waste energy'.

We show how quantitative flow- and heat-transport modeling approaches can offer a scientific basis for thermal management strategies. In combination with geographic information systems, evaluating heat-potential and heat-demand can become the basis for management concepts as well as for the overall economic and ecological thermal planning of subsurface resource usage.

An index which relates groundwater heat-potential to heat-demand is introduced here. This index allows us to quantify the share that thermal 'waste energy' from groundwater resources could have to satisfy heat-demand. On the one hand, we demonstrate how the spatial distribution of this index can be derived for the urban area of Basel, Switzerland. On the other hand, we exemplify the temporal evolution of the heat-potential for selected urban areas and discuss the capacity for space heating with a typical annual heat-demand profile.

1. Introduction

The EU2020 growth strategy has three targets: a 20% reduction of CO_2-emissions by the year 2030, at least a 20% share of renewable energy sources in energy production, and a 20% improvement of energy efficiency by the year 2020. Furthermore, a long-term target of the EU, to the year 2050, is to reduce the greenhouse gas emissions by at least 80% compared to 1990 levels.

However, solutions for reaching such ambitious goals are still lacking. This also is true concerning solutions for how to recover from anthropogenic impacts, such as increased subsurface temperatures, which have been observed in many urban areas.

One environmental vision to reach these goals is the 2000-Watt-Society, which was first introduced in 1998 by the Swiss Federal Institute of Technology in Zürich (ETH Zurich). This program pictures the average First World citizen as reducing their overall average primary energy usage to no more than 2000 Watts by the year 2050, without lowering their standard of living. Generally, the following approaches can be followed to reach that goal: (A) reducing consumption in general (sufficiency), (B) more frequent using renewable energies, and (C) increasing building insulation (efficiency). However, despite progress and more frequent use of renewable energies in recent years,

* Corresponding author.
E-mail address: jannis.epting@unibas.ch (J. Epting).

https://doi.org/10.1016/j.apenergy.2018.06.154
Received 8 March 2018; Received in revised form 22 June 2018; Accepted 30 June 2018

the heat supply in most cities still mainly comes from fossil fuels such as oil and gas.

Shallow subsurface resources are progressively used to produce geothermal energy, i.e. for installing and operating a broad variety of Geothermal Energy Systems (GES). However, in the future, owing to innovative building materials, the demand for geothermal heat from the shallow urban subsurface will decrease, whereas the demand for cooling will increase [1]. Likewise, according to the CH2014-Impacts [2] projects for the lower parts of Switzerland, in non-intervention scenarios (A1B and A2) the number of 'summer days' (average number of days per year with maximum temperatures of 25 °C) and the common occurrence of 'tropical nights' (average number of days per year with minimum temperatures of 20 °C) are expected to increase twofold. Additionally, a lower number of 'heating degree-days' contrasts with a higher number of 'cooling degree-days,' which is a shift that may deeply affect the important energy demand for space heating and cooling. Nonetheless, a greater awareness among politicians and technicians can also be realized regarding the shallow geothermal potential [3].

Thermal groundwater regimes in urban areas are affected by numerous anthropogenic changes, such as surface sealing or subsurface constructions, as well as using groundwater as a cheap cooling medium. Additionally, subsurface infrastructure extensions and the diffuse heat input of heated buildings have resulted in elevated groundwater temperatures observed in many urban areas led to the so-called "Subsurface Urban Heat Island" (SUHI) effect (e.g. in Winnipeg, Canada [4]; Cologne, Germany [5]; Berlin, Munich, Cologne, Frankfurt, Karlsruhe and Darmstadt, Germany [6]; Basel, Switzerland [7]). Today, heating with groundwater (resp. the subsurface in general) is often performed without considering the potential effects it has on subsurface resources as well as the multiple interactions between different subsurface utilizations. This use is currently uncoordinated, so it can cause conflicts among different subsurface users. Furthermore, thermal pollution of subsurface resources specifically may lead to large-scale thermal impacts and impair groundwater quality. Because SUHI strongly influences the thermal regimes of soil and groundwater systems [8], the effects produce a global groundwater quality issue that will worsen in the future. But so far, little is known about groundwater's biological, chemical and physical aspects, and about the influence that increased temperatures have on groundwater quality [9–14].

Applications for Geographic Information Systems (GIS) and hydrogeological mapping approaches are commonly developed to manage urban thermal subsurface resources (e.g. the ThermoMap Project covering 9 countries across Europe [15]; the VIGOR project for South-Italy [16]; as well as projects for the province of Cuneo in the north of Italy [17]; for south-western Germany [18]; and the city of Barcelona in Spain [19]). However, such GIS applications are limited. They cannot capture and adequately represent the high dynamics of hydraulic and thermal subsurface regimes, or the interaction of the different natural and anthropogenic boundary conditions.

Therefore, and especially at the urban scale, we need numerical approaches and we need to develop heat-transport models to manage thermal subsurface resources. However, so far, only a few studies have approached resource management and the exploitation of ground source energy at the scale of urban aquifers (e.g. London, United Kingdom [1]; Basel, Switzerland [20]). Also, most studies do not account for advective heat-transport related to groundwater flow, which is the most important heat-transport process for the spatial (re)distribution of energy in the subsurface, especially in unconsolidated, highly permeable sediments (e.g. [21]).

Therefore, this contribution offers a theoretical consideration for how to manage urban thermal subsurface resources. This is done by means of assessing the heat-potential from urban groundwater resources against the background of heat-demand for the case-study city of Basel, Switzerland.

On the one hand, heat-demand today and tomorrow has been evaluated in the study, 'Basel on the way to the 2000-Watt-Society - A study on the energetic potential of the canton of Basel-Stadt' [22]. For our study, we considered the current state of the heat-demand (2010), and also the situation in 2050 by following the trend 2010 of the Swiss energy policy as well as the 2000-Watt scenario.

On the other hand, this contribution is based on the high-resolution groundwater flow and heat-transport modeling results from the research project called 'Thermal management systems for the shallow subsurface of the Basel region' (Swiss Federal Office for Energy SFOE-Project SI/501044-01). This facilitated our assessment of the heat-potential of the urban groundwater resources in Basel.

By merging heat-potential and the different scenarios of heat-demand, we could theoretically estimate what share of renewal energy resources could be supplemented by using 'waste energy' from urban groundwater resources. We derived an index which allowed us to spatially relate groundwater heat-potential to heat-demand on an urban scale. Furthermore, we exemplify the temporal evolution of heat-potential for selected urban areas and discuss the capacity for space heating with typical annual heat-demand profiles. Our approach presents a first step for how to spatially and temporally optimize the management of urban thermal subsurface resources.

2. Settings, approach and methods

Anthropogenic non-impacted groundwater temperatures should correspond to mean annual air temperatures. For the urban area of Basel (Switzerland), groundwater temperatures of around 10 °C would therefore be expected. However, evaluations in highly industrialized and commercialized areas of Basel show that the groundwater is actually heated up to 16–18 °C [23]. Moreover, during the extremely hot summer 2003, seven tropical nights were already recorded in Basel.

In total, about 50 groundwater users are currently operating in Basel. The total extracted amount of groundwater was about 25.2×10^6 m^3 in the year 2015. 62% of that water was used for drinking water production and 38% for industrial applications. The volume of water used for cooling, which is reinjected back into the aquifer as relatively 'warm' water, has approximately tripled in the last 20 years to about 1.6×10^6 m^3 [20].

Today, the power supply of Basel is almost fully covered by hydropower, and renewable energy only covers a small part of the required heating supply. In addition to hydropower, wind power, and solar energy, waste (50% renewable) is used for heat and power generation.

2.1. Quantification of heat-demand

In the scope of the study called 'Basel on the way to the 2000-Watt-Society - A study on the energetic potential of the canton of Basel-Stadt' [22], the energy resources and heat-demand in Basel were evaluated, and the sectors were distinguished between housing, working and living. The working sector is divided into commerce, trade and services, as well as industry. All the three sectors are associated with different forms of energy (heat, electricity, fuels). Aspects of mobility have not been considered.

The energy model developed considers the spatial and temporal energy demand, and also relates it to renewable energy supply potential. Therefore, in a first step, the urban area was divided into urban spatial prototypes which have a characteristic energy demand, but also a prototypical potential to provide renewable energy.

As a baseline, the heat-demand E_D [GWh ha^{-1} a^{-1}] for the situation in the year 2010 was delineated. In order to investigate if and when Basel reaches the goals of the designated 2000-Watt-Society, future scenarios were designed.

(A) A reference scenario represents the energetic development of Basel following the current trend of the Swiss energy policy (at the time the study was performed). The underlying assumptions are