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GIS-based modelling of shallow geothermal energy potential for CO_2 emission mitigation in urban areas

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ABSTRACT

Due to the rapidly increasing percentage of the population living in urban centres, there is a need to focus on the energy demand of these cities and the use of renewable energies instead of fossil fuels. In this paper, we develop a spatial model to determine the potential per parcel for using shallow geothermal energy, for space heating and hot water. The method is based on the space heating and hot water energy demand of each building and the specific heat extraction potential of the subsurface per parcel. With this information, along with the available space per parcel for boreholes, the percentage of the energy demand that could be supplied by geothermal energy is calculated. The potential reduction in CO_2 emissions should all possible geothermal energy be utilised, is also calculated. The method is applied to Ludwigsburg, Germany. It was found that CO_2 emissions could potentially be reduced by 29.7% if all space heating and hot water requirements were provided by geothermal energy, which would contribute to the sustainability of a city. The method is simple in execution and could be applied to other cities as the data used should be readily available. Another advantage is the implementation into the web based Smart City Energy platform which allows interactive exploration of solutions across the city.

1. Introduction

By 2030 it is predicted that almost 60% of the world's population will live in urban areas. In the European Union (EU) 74% of the total population lives in areas classified by national statistical offices as urban.[2] With such growth in urban centres, sustainability has become a key concept when planning for the future. Since the Brundtland report [30] sustainability issues are on the political agenda, particularly CO_2 emissions and the depletion of fossil fuels through rising fuel consumption of growing cities. The EU has recognised this need in their EU2020 growth strategy [12] which aims at reducing CO_2 emissions by 20%, increasing the share of renewable energy sources in energy production to 20% and improving energy efficiency by 20% 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% as compared to 1990 levels. The need to approach urban planning with a view to not placing excess strain on land and resources is now widely accepted. However, in order for cities to ensure the sustainability of their energy production and use, renewable energy sources need to be included in urban growth plans. As a consequence, the European project MUSIC[3] was launched to address CO_2 reduction by renewable energy potentials within the five cities Aberdeen, Ghent, Ludwigsburg, Montreuil and Rotterdam. A web based decisions support system, the Smart City Energy Platform, was developed to enable multiple end users to explore sustainable solutions based on renewable energy potentials across the entire city at a high resolution.

It has become necessary to assess the energy demand at urban scale, and the potential for using different renewable energy sources to fulfil this demand. One should determine which renewable energy type, or mix, would be best suited to a city, as well as the impact this would have on reducing CO_2 emissions. Shallow geothermal energy is one alternative that has received less focus than wind and solar energy potentials for cities. We address this gap with a particular focus on how the density and forms of

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[1] WP2 leader iGUESS, the MUSIC project. URL: http://www.themusicproject.eu.
[2] World Bank data http://data.worldbank.org/topic/urban-development.
[3] The MUSIC project http://www.themusicproject.eu.

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urban pattern impact on energy potential and capacity to meet consumption demand.

Solar and wind energy have been the main focus of attention of studies into the potential for using these renewable energy sources. Geographical information systems (GIS) have been used for suitability mapping of land cover classes with high solar and wind energy potential [3,15,24,29]. Most studies are focused at a regional scale. Voivontas et al. [29], for example, calculated the water heating demand for a residential region, as well as the potential for using solar energy to meet these demands. Assessments of solar energy potential have also been performed at urban scale by Bergamasco and Asinari [4], who developed a simple methodology for assessing the roof-top potential for solar panels for the city of Turin, while Brito, Gomes, Santos, and Tenedo'rio [8] developed a procedure to estimate the photovoltaic potential of an urban region using LiDAR data and the Solar Analyst extension for ESRI's ArcGIS. Mastrucci et al. (2015) [20] applied the Smart City Energy Platform for the combined assessment of housing electricity consumption and PV potential at the urban scale for the City of Rotterdam.

Compared to wind and sun, shallow geothermal energy is much less well studied despite it being a potentially good choice due to its unlimited availability. It is able to provide energy year round and is not dependent on outside factors such as cloud cover as for solar panels, or wind for wind turbines. The use of geothermal energy is becoming increasingly popular, with an estimated installed thermal power for direct utilisation in 2009 of 48,493 MWt, showing an annual growth from 2005 to 2010 of 11.4%. This equates to an energy saving of 250 million barrels of oil, annually, and a reduction in CO_2 of 107 million tonnes [18]. The leading countries in installed units for direct use are the US, China, Sweden, Germany and the Netherlands. However, there is slow development of this energy resource due to the high cost of installation and the current economic downturn hampering spending [19].

The question addressed in this paper is how to easily assess the potential for replacing fossil fuels with shallow geothermal energy in order to satisfy the space heating and hot water demand of a city. We use a geographical approach as, at city scale, the urban pattern is relevant to the demand and the space available for the installation of borehole heat exchangers. The potential calculation is assessed on a parcel by parcel basis, which is intensive at this scale and therefore a simple GIS (geographical information system) method was required to carry this out. We use a sampling method to determine how many boreholes could fit onto each parcel and determine what percentage of the energy demand can then be supplied by geothermal energy. Following this, we determine the potential reduction in CO_2 emissions if all possible geothermal installations are put in place within the city. The outcomes of such an analysis can be used by urban planners within the MUSIC project when developing more sustainable master plans for the city, in accordance with the EU2020 strategy. Easily obtainable data have been used in the methodology to ensure that the process is replicable in any city of the MUSIC project and beyond with access to the same basic data.

Due to the readily available dataset, the city of Ludwigsburg was used as a case study. The developed methodology will be the basis for a web based online calculator within the Smart City Energy Platform[4] which is based on the software framework iGUESS [1]. The article is organised as follows. In Section 2, we introduce shallow geothermal energy technology and review the literature on the assessment of its potential as a renewable energy source. In Section 3, we introduce the data and the case study area of Ludwigsburg. Following this, we present a sequence of computational methods, namely the calculation of energy demand, the geothermal potential and the percentage of the energy demand satisfied by geothermal energy at parcel level. We then calculate the potential reduction in CO_2 emissions at city scale. In Section 4, we present the results for each submodel. In Section 5, we conclude that the methodology for determining the geothermal potential of a city is simple and effective and that a significant reduction in CO_2 emissions can be achieved through using geothermal energy for space heating and hot water. We also conclude that residential dwellings are best suited to this type of renewable energy as the energy demand is relatively low and there is enough space available for the installation of a borehole on the parcel to cover this demand. This questions the design of sustainable residential neighbourhoods in terms of compactness or density planning – in certain cases, where shallow geothermal energy can be utilised, a less dense urban pattern would be considered more sustainable.

2. Shallow geothermal energy

Geothermal energy in general terms refers to the energy stored in the earth in the form of heat. It is a huge, largely untapped renewable energy resource that will never be depleted [28] and bears no associated CO_2 emissions. We need to evaluate the potential of this energy source for cities and this requires a good understanding of the processes and techniques as well as identifying knowledge gaps within the existing literature.

2.1. Processes, techniques and definitions

Due to the high cost of installation of shallow geothermal energy heat extractors (e.g. borehole heat exchangers, ground source heat pumps) it is important to have an idea of the potential of the ground to yield geothermal energy, and whether it is enough to cover the energy demand at that point. The amount of geothermal energy available at any location is dependent on a number of factors, the two most important being the solar radiation received by the ground and the type of rock found at that location. Different rock types store and conduct heat differently and these factors influence the temperatures of the ground at a location and therefore the energy available for extraction. Other factors which can influence this are elevation, aspect of slopes, vegetation cover, climatic conditions and the presence of groundwater [25] (see Fig. 1).

Temperature of rock or soil at and near the surface of the earth relies almost entirely on heating by the sun and cooling through radiation and evaporation and various heat-absorbing processes. At any location the temperature is a function of heat from below (geothermal gradient) and solar input. The effect of the sun decreases with depth. The temperature of the upper few metres of the subsurface is usually a few degrees lower than the air temperature in summer, and a few degrees warmer in winter due to the time lag of the ground adjusting to the ambient temperature [17]. The temperature of the subsurface increases with depth according to the geothermal gradient and below approximately 10–15 m, the ground temperature remains constant year round and therefore offers a good source of energy for space heating and cooling (see Fig. 2).

Shallow geothermal energy, on which we focus here, utilises the temperature gradient between the ambient air and the upper 400 m of the subsurface for the heating or cooling of buildings. As the temperature between the air and ground differs by a few degrees, this difference can be exploited to extract energy. This warmth of the ground compared to the air (as for example, in winter) is used to heat a fluid (through conduction) running through a pipe inserted in a borehole in the ground. Heat from the fluid is then extracted by a heat pump and used to heat a building

[4] Smart City Energy Platform http://iguess.list.lu.