Renewable Energy 86 (2016) 1023–1036

Contents lists available at ScienceDirect

Renewable Energy

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

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

Kerry Schiel [a,*], Olivier Baume [b], Geoffrey Caruso [a], Ulrich Leopold [b,1]

[a] University of Luxembourg, Maison des Sciences Humaines, 11 Porte des Sciences, L-4366 Esch-Belval, Luxembourg
[b] Luxembourg Institute of Science and Technology, 5 Avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg

ARTICLE INFO

Article history:
Received 13 July 2015
Accepted 7 September 2015
Available online 24 September 2015

Keywords:
GIS
Urban planning
Energy demand
Geothermal energy
iGuess
Smart city energy

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

* Corresponding author.
E-mail addresses: kerry.schiel@uni.lu (K. Schiel), Ulrich.Leopold@list.lu (U. Leopold).
[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.

http://dx.doi.org/10.1016/j.renene.2015.09.017

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.

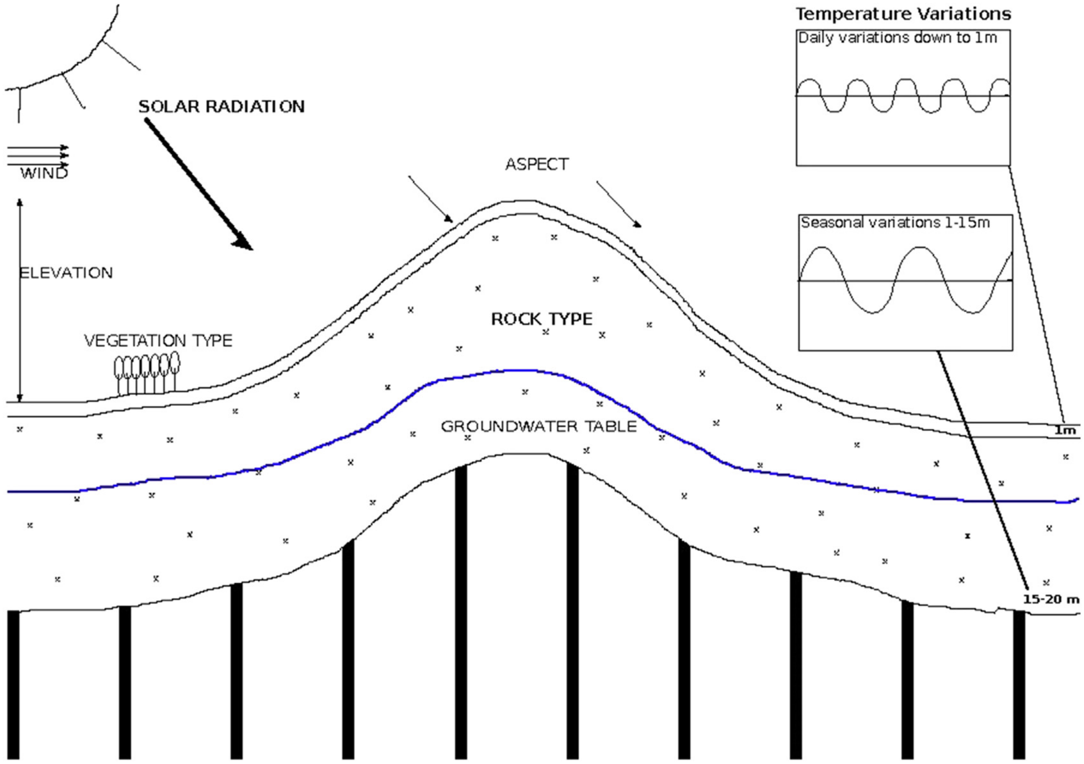

Fig. 1. Influences on ground surface temperature and subsurface temperature variations.

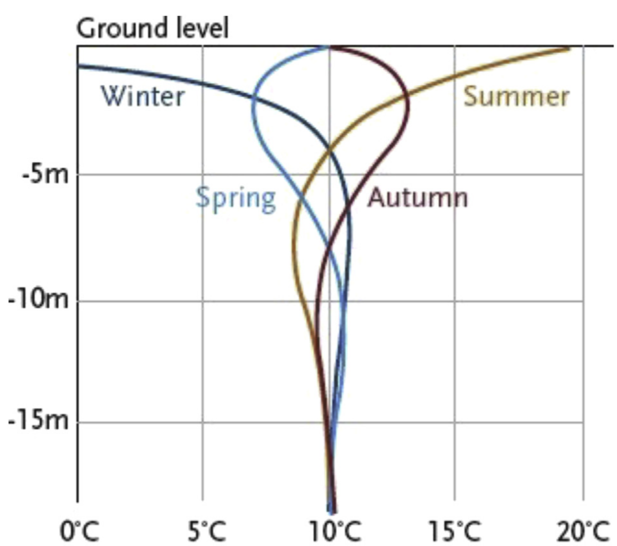

Fig. 2. Approximate UK annual ground temperature (www.cibsejournal.com/cpd/2010-04 [11]).

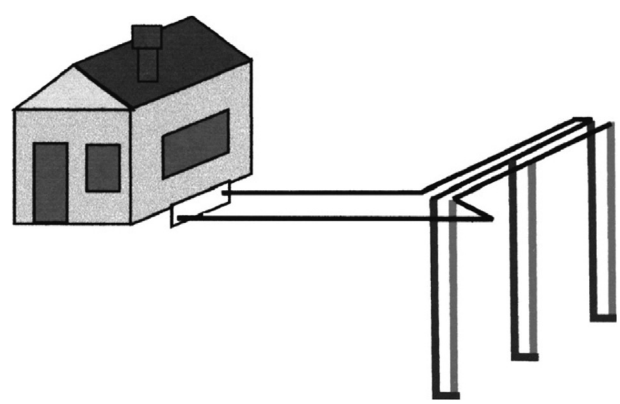

Fig. 3. Vertical Closed Loop Borehole Heat Exchanger [27].

and provide hot water. In summer, the cooler ground is exploited as a heat sink for warm air removed from a building. It only requires the use of electricity to run the heat pump which extracts the heat from the geothermal energy system [25].

The extraction of shallow geothermal energy can be done through horizontal or vertical systems in an open or closed loop. In this study we focus on vertical closed loop borehole heat exchangers (BHEs) (see Fig. 3), as these systems can reach depths where the temperature remains constant (below ± 10 m) and also do not require large amounts of space for installation – hence they are arguably more suited to urban environments. The BHEs are typically 50–100 m deep.

The BHEs have to be designed according to local conditions. There are two main factors on which the borehole will be sized: the energy demand of the building (heating or cooling could be the primary demand depending on the climate at that location) and the heat extraction potential of the borehole (i.e. the amount of geothermal energy the rocks can supply).

The overall potential for heat extraction in a rock is expressed as the specific heat extraction (sHE) of energy in Watts per metre of borehole length. This value depends on factors such as mineralogy (rock type), porosity (higher porosity lowers values) and the presence of groundwater (groundwater facilitates the transfer of heat) [14].

The combined sHE values for each of the rock layers at any location can be calculated to determine the amount of energy

Table 1
Typical heating demand values per settlement type.

Settlement types	Description	GWh/km^2a	kWh/m^2a
ST 1	Loose open development	25.5	57.7
ST 2	1 and 2 family house settlement	45.6	111.6
ST 3	Village core	52.5	85.0
ST 4	Terraced houses	42.5	62.6
ST 5a	Small apartment buildings	64.5	130.9
ST 5b	Small and medium apartment buildings	78.5	181.1
ST 6	Skyscrapers	101.3	145.7
ST 7a	Loose block developments	104.3	158.9
ST 7b	Dense block developments	106.5	157.2
ST 8	City buildings	117.8	102.3
ST 9	Historical old town	101.2	170.0
ST 10a	Large special public buildings	101.7	207.1
ST 11b	Commercial and service buildings	125.3	913.7

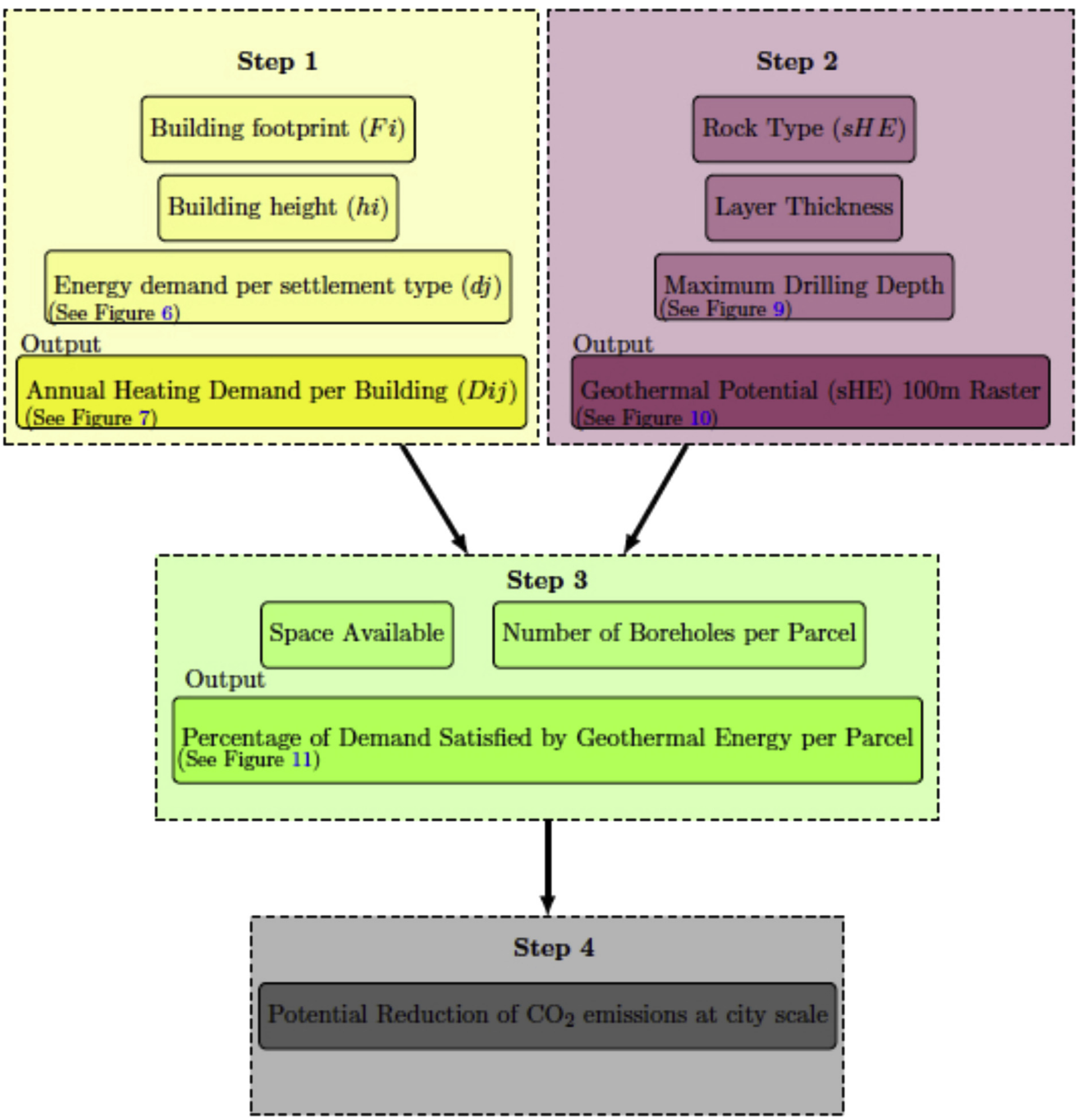

Fig. 4. Steps followed within the Methodology.

Table 2
Possible specific heat extraction for borehole heat exchangers (4640 Richtlinie VDI [2]).

General guideline values	Specific heat extraction (W/m) for 2400 h
Underground(λ = thermal capacity)	
Poor underground (dry sediment) ($\lambda < 1.5$ $W/(m.K)$)	20
Normal rocky underground and water saturated sediment ($\lambda < 1.5$–3.0 $W/(m.K)$)	50
Consolidated rock with high thermal conductivity ($\lambda > 3.0$ $W/(m.K)$)	70
Individual Rocks:	
Gravel, sand, dry	<20
Gravel, sand, saturated water	55–65
For strong groundwater flow in gravel and sand, for individual systems	80–100
Clay, loam, damp	30–40
Limestone (massif)	45–60
Sandstone	55–65
Siliceous migmatite (e.g. granite)	55–70
Basic migmatite (e.g. basalt)	35–55
Gneiss	60–70

*The values can vary significantly due to rock fabric such as crevices, foliation, weathering, etc.

Table 3
Rock formations and associated specific heat extraction (sHE) values.

Layer name	Formation name	Predominant rock type	sHE Value (2400 h) (W/m)
S22	Quaternary	Loose gravel, sand, silt and clay sediments	20
S55	Upper middle Keuper (Schilfsandstein)	Sandstone, claystone, dolomite	55
S60	Gipskeuper	Claystone, dolomite, gypsum/anhydrite	55
S70	Lettenkeuper	Claystone, dolomite, sandstone	45
S75	Upper part of upper Muschelkalk lower part of upper	Limestone, dolomite, partly claystone	45
S76	Muschelkalk and upper dolomite of the middle Muschelkalk	Limestone, dolomite, partly claystone	45
S90	Gypsum formation of the middle Muschelkalk	Gypsum/anhydrite, dolomite	40
S100	Lower Muschelkalk	Limestone, marl, dolomite, partly claystone	45

potential available at that point up to the maximum allowed drilling depth. This will be discussed further in the section on methodology.

The heat pump is used to extract the heat from the heated fluid by reversing the natural flow direction of heat through the use of a compressor. A heat pump uses less electricity to extract the heat than when converting electrical energy into radiant energy, e.g. in radiant heaters. The efficiency of the heat pump depends on the quality of the components used and the temperature gradient between the incoming fluid and the desired temperature in the building. This efficiency is called the coefficient of performance (CoP) and is the ratio of useful energy (energy produced) to the electricity consumption of the pump. The seasonal performance factor refers to the overall performance of the heat pump over a whole season.

2.2. State of the art

Previous studies have been done using GIS to assess the geothermal energy potential. However, these studies have mostly been aimed at deep geothermal energy and energy from hot springs and aquifers, and were done at a regional scale for the siting of large-scale geothermal plants. Blewitt et al. (2002) [6] assess the potential through the creation of geological models to determine the relationship between strain rates, faults and the presence of deep geothermal power-producing sites. Coolbaugh et al. (2003) [9] provide an accessible database containing geothermal temperature maps, as well as a predictive map of geothermal potential based on areas of high extensional strain rates and high heat flux in order to predict regions which are likely to have high geothermal energy potential. This was performed at a national scale and was also based on deep geothermal energy. Lashin (2014) [16] uses analysis of satellite imagery and a geothermic study, as well as a 2D electric study for the detection of geothermal reservoirs with hot water reserves of 46–78 °C. This study was done for the south western region of Saudi Arabia. Noorollahi (2008) [22] developed a GIS decision support tool to determine the spatial association exploration and environmental thematic mapping, which include analyses of geological, geochemical and geophysical information on a regional scale, in order to determine the potential for using deep geothermal energy. The tool includes site selection by overlaying potential and environmental suitability analysis, for the selection of suitable geothermal energy fields.

Two further studies on assessing the geothermal potential at regional scale were done by Ondreka et al. (2007) [23] and Gemelli et al. (2011) [14]. Ondreka et al. (2007) produced geothermal potential maps for two case study regions in south-western Germany, which took the thermal properties of the subsurface into account (based on the geology and hydrogeology). The subsurface was divided into layers with similar thermal properties and assigned a specific heat extraction value, and maps of the weighted average at depths of 50 m and 100 m were calculated. They showed with these maps, how the specific heat extraction varies between areas and depends on depth. Gemelli et al. (2011) used a regional geothermal potential map, derived from physical parameters, to calculate a set of economic indicators to evaluate the actual economic accessibility to the geothermal energy resource.

Overall we see there is, therefore, a need for developing a spatial model which can be used at local scale to determine the potential for utilising shallow geothermal energy, which is readily available for exploitation all over the world and takes into account variations in the potential energy based on the underlying geology.

The advantage of using a renewable resource such as shallow geothermal energy is the reduction in CO_2 emissions. Blum et al. (2010) [7] assessed this potential at regional scale for the south west of Germany and found that savings of 35% were possible for

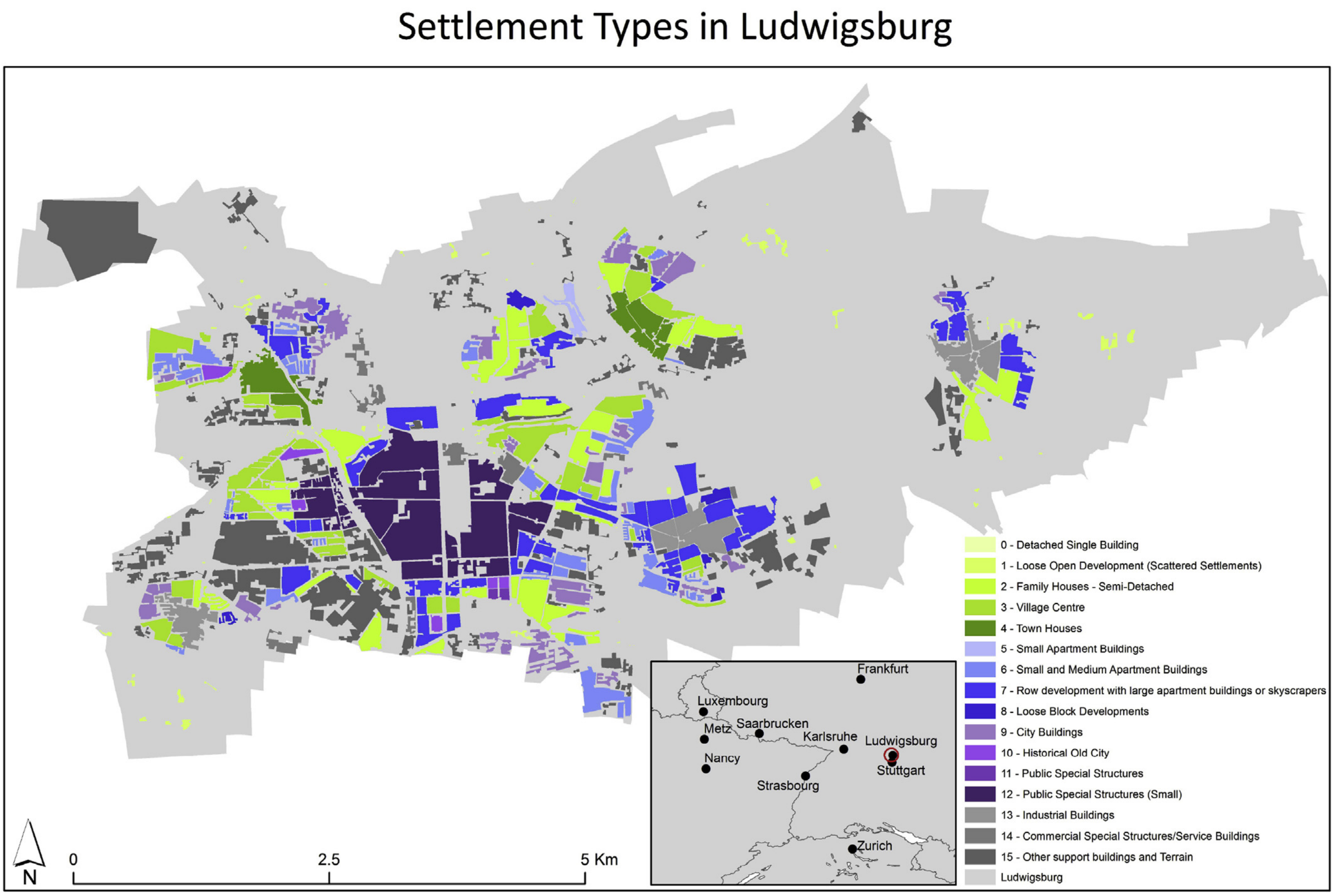

Fig. 5. Distribution of settlement types in Ludwigsburg.

the national electricity mix and 72% for the regional electricity mix. The savings depended heavily on the electricity required for the heat pumps, as well as the efficiency of the installation of the borehole heat exchanger. They conclude that additional CO_2 emissions can be avoided through the use of shallow geothermal energy for the heating (and cooling) of buildings. Sauer et al. (2010) [26] concluded from their life cycle assessment of geothermal installations that the CO_2 savings from geothermal energy depends predominantly on the electricity used by the heat pump, climatic conditions and the inclusion of passive cooling capabilities, with minor contributions through leakage of heat carrier fluid into the ground and the degradation of the efficiency of the heat pump.

The originality of the work lies in the combination of a GIS model to determine the potential for using geothermal energy, with an assessment of the possible reduction in CO_2 emissions that this could lead to, should geothermal energy be implemented for space heating and hot water.

3. Data and methodology

3.1. The case study: Ludwigsburg

The work presented in this article is based on data from the city of Ludwigsburg, one of the 5 partner cities in the MUSIC project,[5] which aims at helping these cities reduce CO_2 emissions by 20% by the year 2020.

Ludwigsburg is a city of approximately 87,000 inhabitants, situated north of Stuttgart. The city has had an energy plan since 2004 and is very forward thinking in its approach to climate change, renewable energies, energy security and local air quality [13].

Ludwigsburg is part of Baden-Wűrttemburg where there are two main geological units – the crystalline basement and the sedimentary overburden. The basement rocks are composed mainly of gneisses and granites. The sedimentary overburden covers the crystalline basement and was deposited in a variety of ways and settings.

In Ludwigsburg, the main rock types encountered are the lacustrine, fluvial and marine sediments of the Buntsandstein (251–243 Ma), Muschelkalk (243–235 Ma) and Keuper formations (235–200 Ma).

The main rock types associated with these formations are sandstone, mudstone, limestone, dolomite, gypsum/anhydrite and loosely consolidated sand and clay. It is important to know the predominant rock types in a formation and the layer thicknesses as these will influence the total specific heat extraction value associated with that rock formation.

3.2. Methodology

The method developed in this study included 4 steps: to calculate (1) heat demand, (2) specific heat extraction, (3) the percentage of the demand satisfied by geothermal energy per parcel and (4) the potential reduction in CO_2 when utilising geothermal energy for space heating and hot water. It was kept simple in order to be easily replicable for other cities with access to the same data. There are

[5] The MUSIC Project, http://www.themusicproject.eu.

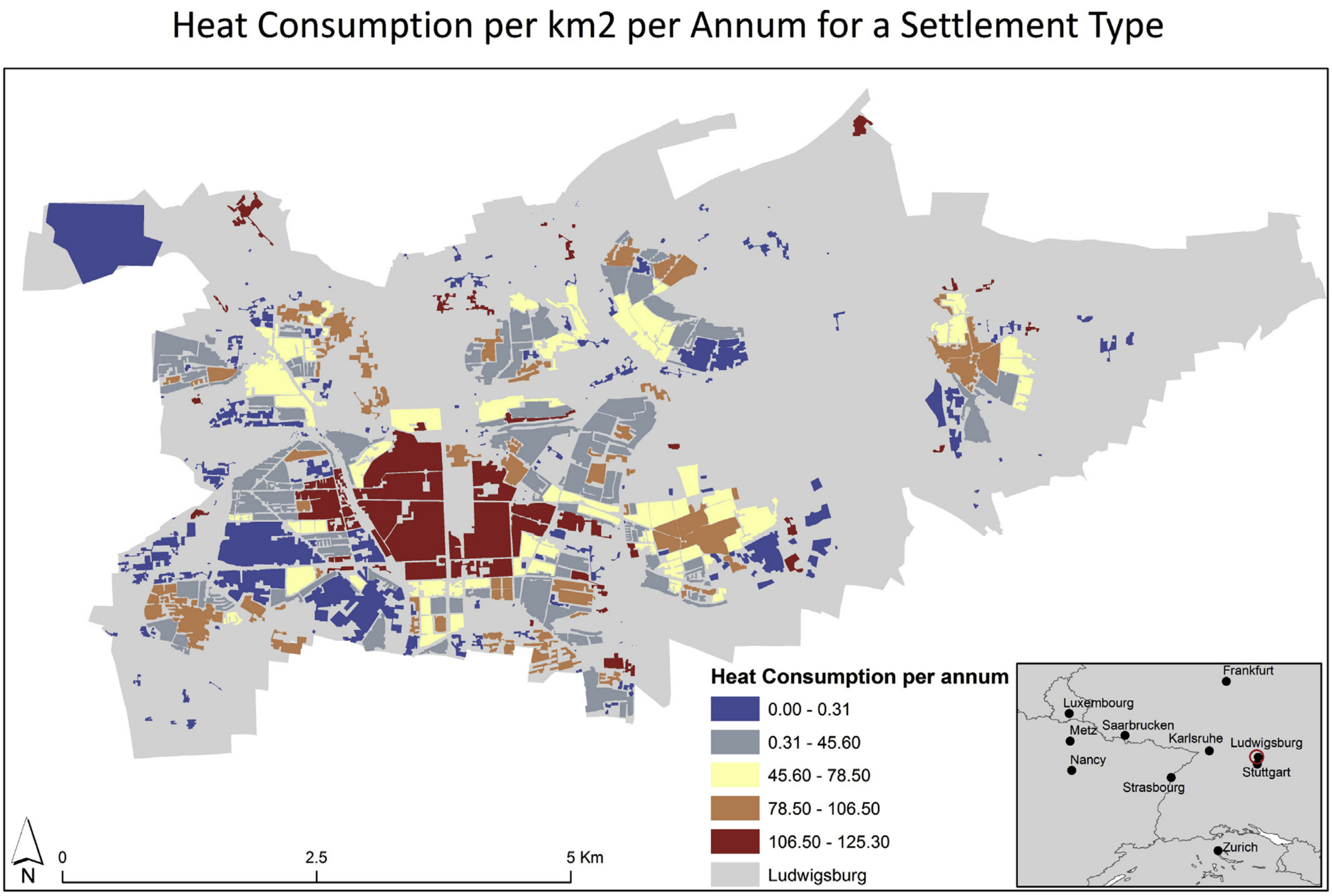

Fig. 6. Energy demand per settlement type in Ludwigsburg (d_j) (GWh/a).

four sections to the methodology. Firstly, we calculated the hot water and space heating energy requirements per parcel based on the volume of the building and the associated energy demand values per settlement type into which the building falls. A settlement type is a combination of different building types within a certain area, e.g. the city centre which contains many different types of buildings (see Table 1). We used a settlement typology developed by the University of Stuttgart's Institute of Economics and the Rational Use of Energy (IER) [5]. Zonal data on settlement type was disaggregated in order to have an energy demand value per building. This was done by transforming a consumption value for a settlement type zone per square kilometre into a consumption value per building falling within a settlement type.

Secondly, the specific heat extraction potential of the subsurface was calculated using interpolated borehole data (rock type and layer thicknesses), along with maximum allowable drilling depth, in order to determine the amount of energy that could be extracted down to the maximum drilling depth.

Thirdly, these results were used, along with results from a sampling process, to determine the number of boreholes which could fit on each parcel, the number and length of boreholes required to fulfil the space heating and hot water energy needs, as well as the percentage of the energy requirements which could be provided by shallow geothermal energy per parcel. Finally, the potential reduction in CO_2 emissions by providing all space heating and hot water requirements with shallow geothermal energy was calculated by determining the contribution of CO_2 emissions by space heating and hot water and determining the percentage of the total emissions these make up, in order to determine the potential reduction.

Fig. 4 shows the steps that were followed to achieve these objectives.

3.2.1. Heat energy demand calculation (step 1)

The methodology follows the one described by Dorfner (2011) [10]. The following data was used for the calculation of the heat energy demand for hot water and space heating per building: Building footprints, F_i; building height, h_i and the space heating and hot water energy demand per building based on settlement type, d_j. In this typology, buildings are assigned a heat consumption according to the settlement type into which they fall. Each settlement typology has an annual heat consumption density value, in GWh/a. A value per square kilometre of settlement type was calculated based on the total area of each settlement type (GWh/km^2a). This was then converted to a value per building based on the size of the building and the settlement type into which it falls (kWh/m^2a). We obtained a range of values from 40 to 455 kWh/m^2a that belong to the common values of space heating demand per square metre per annum (Table 1).

The space heating and hot water demand per building (D_{ij}) was calculated as follows:

$$D_{ij} = 1.2 d_j A_i \quad (1)$$

where d_j is the heating demand associated with a particular building type in kWh/m^2a, and A_i is the total area of a building. 20% of this demand is added on in order to account for the additional energy required for hot water. The value of 20% is an assumption

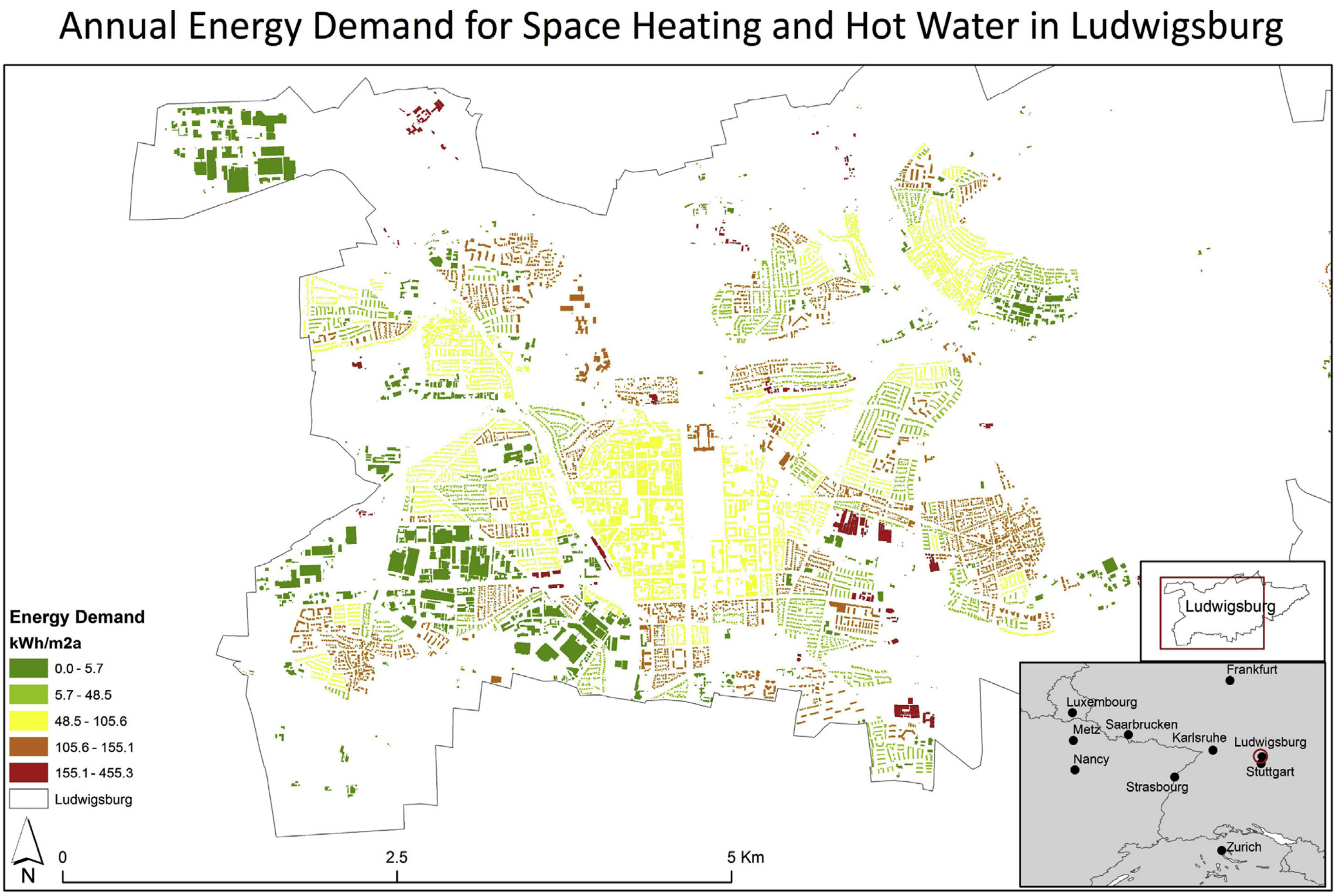

Fig. 7. Calculated annual heating demand per parcel (D_{ij}) (MWh/a).

based on local measurements. The area of the building is calculated by the equation:

$$A_i = F_i n_i \tag{2}$$

where F_i is the area of the building polygon and n_i is the number of storeys in the building.

The number of storeys in a building was calculated using the following equation:

$$n_i = 0.32(h_i - 2.5m) \tag{3}$$

where h_i is the height of the building in metres and is multiplied, as per Dorfner (2011), by 0.32 which equates to an average storey height of 3,125 m. 2.5 m is subtracted from the height to correct for the roof space, which is not included in the area which needs space heating.

The building-footprint and building-height vector data were received from the City of Ludwigsburg. Buildings were excluded from the calculation when height information was missing.

3.2.2. Geothermal energy potential calculation (step 2)

The geothermal energy potential was calculated by determining the specific heat extraction potential in the subsurface of Ludwigsburg, using a 3D subsurface model compiled from borehole data provided by the Geological Survey of Freiburg.[6] The 3D model was provided as a set of points with x, y coordinates and associated attribute data including elevation, depth of the base of each geological formation, petrography, stratigraphy and the maximum allowable drilling depth at each point.

The specific heat extraction (sHE) of each layer was calculated by multiplying the thickness of the layer by the sHE value given in the VDI (Verein Deutsche Ingenieure) guidelines for the rock type best suiting the predominant rock type found in the formation (results in Watts) and summing the values for each layer down to the maximum drilling depth allowed. Typical values are between 40 and 70 W/m. The sHE for each rock type can either be calculated accurately from onsite measurements for larger systems, or, as in our case, by using estimates calculated by the VDI [2] in Germany for each major rock type. The VDI have a set of guidelines called "Thermal Use of the Underground – Ground Source Heat Pumps" which list specific heat extraction values for different general rock types. These estimates are based on different annual operating hours – 1800 or 2400 h. In this case we consider 2400 h to be a realistic estimate of the number of hours required for space and hot water heating over a year in Germany. Table 2 lists the specific heat extraction values for general rock types as determined by the VDI.

Table 3 shows the rock formations, rock type and associated sHE value for those formations found in the Ludwigsburg area, the values for which have been derived from Table 2. The lower end of the range given by the VDI was used in calculations as it is better to underestimate the geothermal potential available, rather than to overestimate [23].

The total sHE potential, derived from the above parameters, was

6 http://www.lgrb.uni-freiburg.de/lgrb/home.

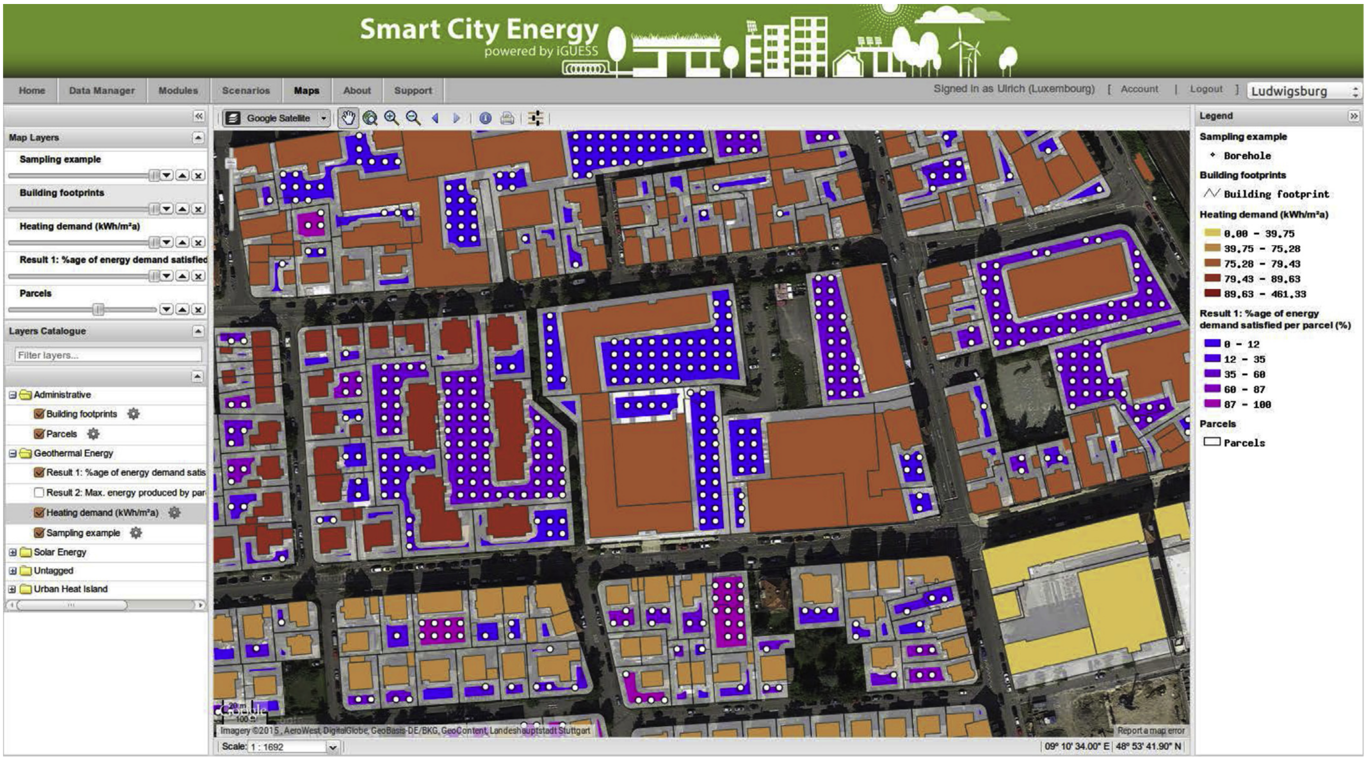

Fig. 8. Heating demand and energy covered by geothermal potential is displayed in the Smart City Energy Platform for each cadastral parcel. Sampling example shows potential boreholes as white circles respecting the interdistance of 6 m and the 3 m buffer from the cadastral parcel edge.

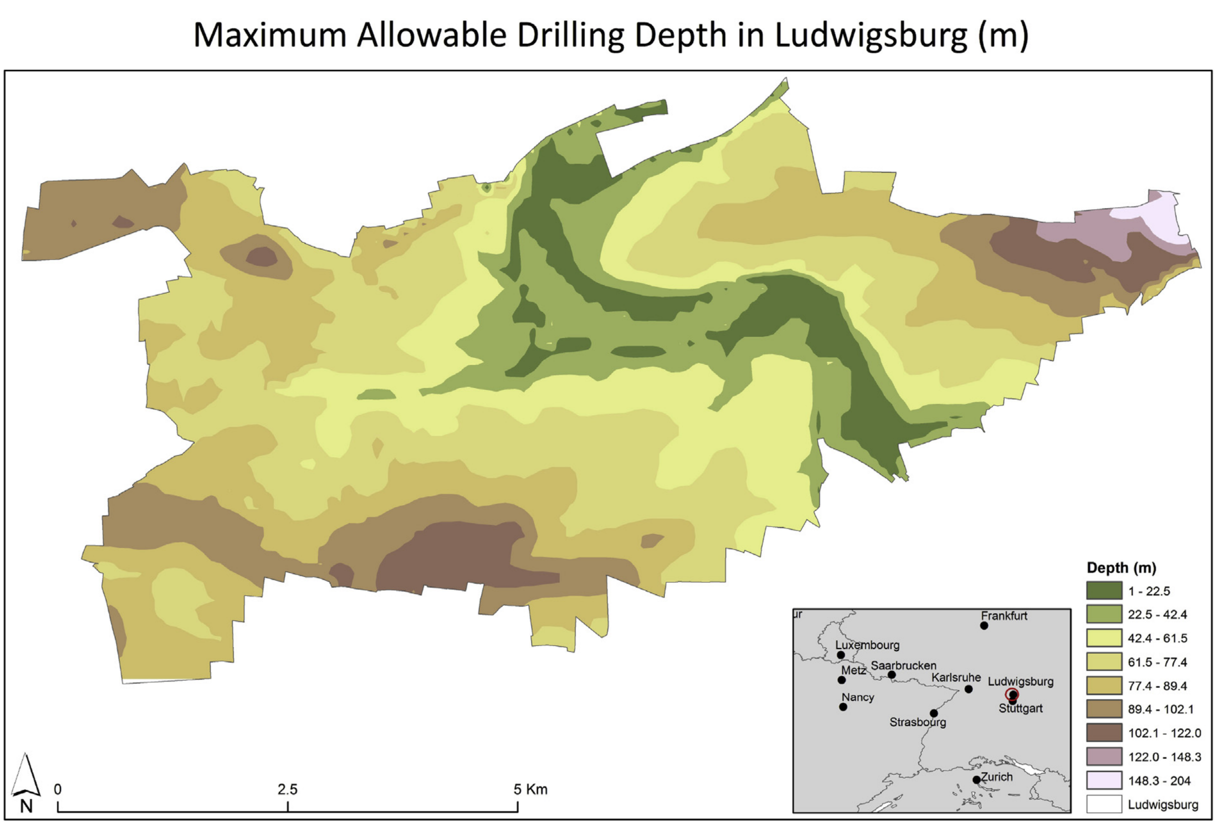

Fig. 9. Maximum drilling depth (m).

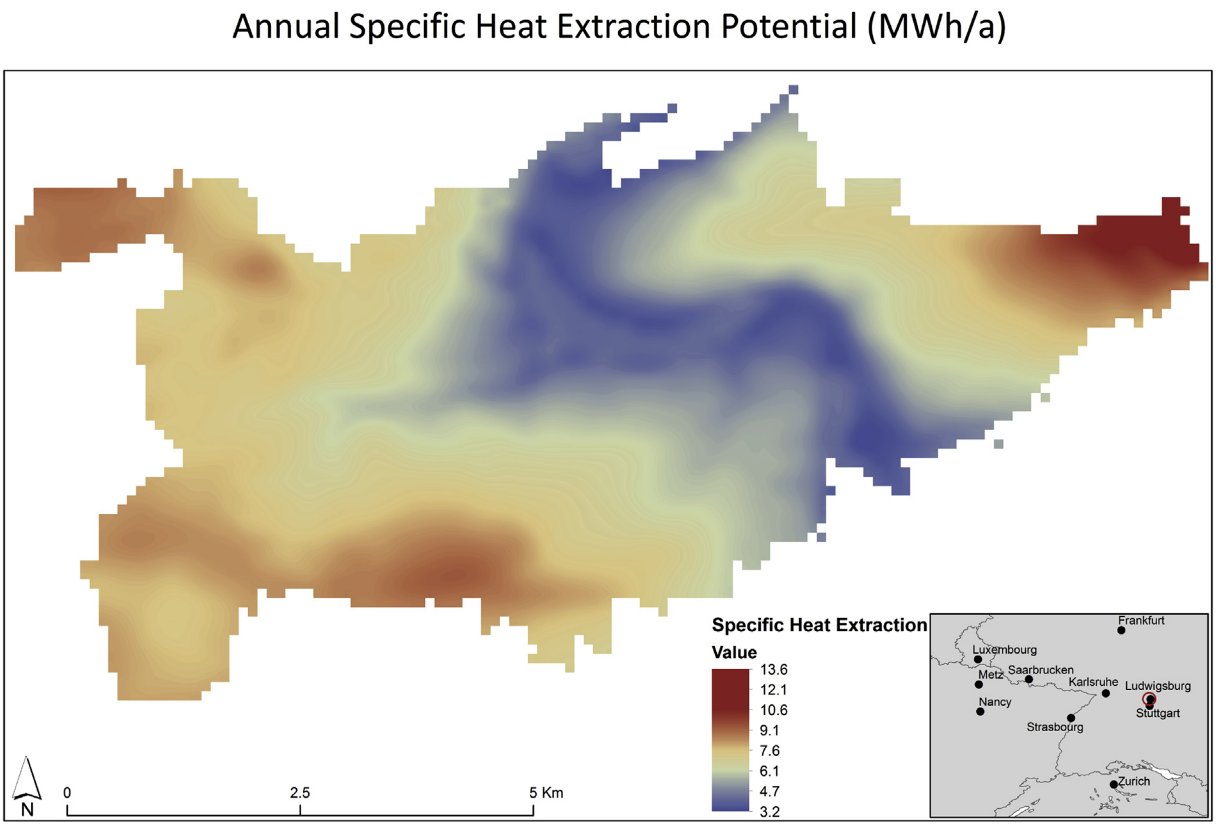

Fig. 10. Calculated geothermal potential (sHE) (*MWh/a*).

then multiplied by 2400 working hours of the borehole per annum, to get an annual sHE potential at each point (values in *MWh/a*).

3.2.3. Demand satisfied by geothermal energy per parcel (step 3)

The next step was to determine the number and lengths of boreholes per parcel of land in order to supply enough geothermal energy to satisfy the demand of the building at that location. For this calculation the energy demand per building (D_{ij}), the heat extraction potential of the corresponding parcel (sHe) and the space available for the installation of boreholes were required. The first two were calculated as described above, while the latter refers to the space left on a parcel once the building and a buffer zone of 3 m has been removed. This was calculated by extracting the building footprints from the parcels and removing a buffer of 3 m around the parcel and building boundaries in order to delineate the area available for boreholes.

To calculate the number of boreholes that could fit onto the available space, a sampling procedure was used to randomly place a regular grid of points spaced 6 m apart over the available space. 6 m was chosen as a suitable distance between boreholes to avoid thermal depletion for boreholes of lengths of 50–100 m [21]. This process was repeated 10 times and the number of points falling within each polygon counted each time. For more realistic results, we used the minimum number of boreholes counted within each parcel, after all iterations were complete, as this would eliminate those polygons with odd shapes and very small areas which would not realistically be used for the installation of boreholes.

Given the number of boreholes that can fit per parcel, the number required, assuming all boreholes would be drilled to the maximum allowable drilling depth, was calculated in order to determine the percentage of the energy demand per parcel that could be satisfied through geothermal energy. Depending on the demand and the size of the parcel, not all boreholes that could fit on the parcel would be required, and sometimes lack of space would mean the demand could not be satisfied. This calculation was carried out using an R-script that is available upon request from the authors.

3.2.4. Potential CO_2 emissions reduction (step 4)

We then evaluated the potential reduction in CO_2 emissions if shallow geothermal energy is utilised for space heating and hot water. In order to determine what this potential is it was necessary to first determine the CO_2 emissions associated with space heating and hot water, as well as from the heat pump. This would detract from the total CO_2 emission reduction benefit. A CoP of 3.2 was used, i.e. for every 3.2 kW of energy produced by the heat pump, 1 kW of electricity is used to extract this energy. The CO_2 emissions were calculated by multiplying the energy consumption by the associated CO_2 emissions (in grams of CO_2 per annum). For the portion of space heating and hot water contributed by electricity, it was necessary to separate the electricity into the various producers (e.g. nuclear, natural gas etc). This was done according to the average electricity mix for Germany.[7]

From these values, the percentage of total CO_2 emissions from space heating was calculated (minus the CO_2 from the use of the heat pump) resulting in the potential percentage for reduction of CO_2 emissions should all possible geothermal energy be utilised. These values were calculated by multiplying the current final energy consumption for space heating and hot water per carrier by the associated value for CO_2 emissions (in *g/kWh*) for that particular carrier. The CO_2 emission values per carrier were then summed.

[7] http://www.unendlich-viel-energie.de/en/details/article/4/the-electricity-mix-in-germany-2010.html.

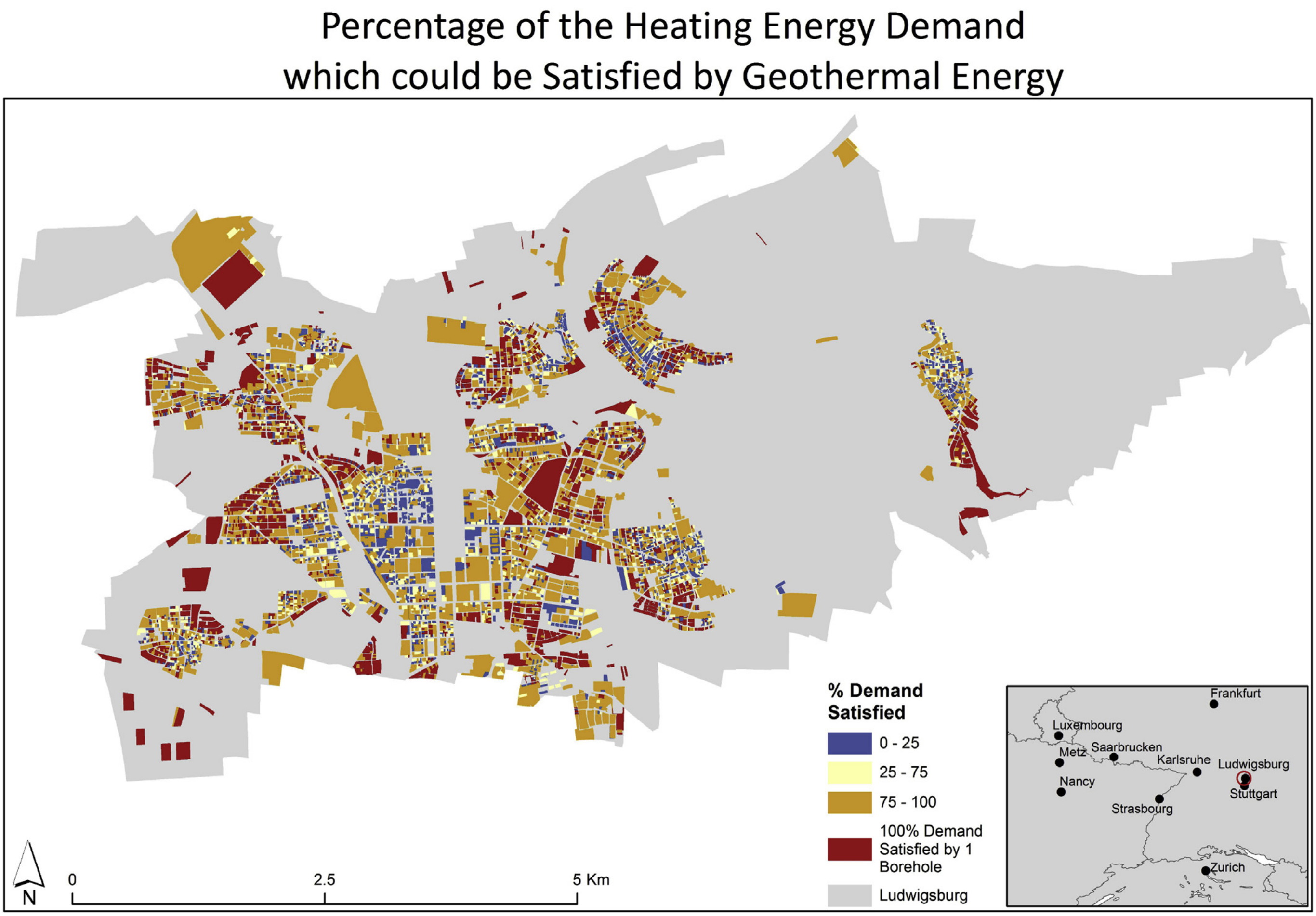

Fig. 11. Percentage of the Heat Energy Demand that can be Satisfied by Geothermal Energy per Parcel.

Table 4
Calculation of CO_2 emissions contributed by energy consumption for space heating and hot water.

Energy carrier	Electricity mix	Percentage contributed to electricity mix	Final energy consumption for space heating and hot water (*Gwh/a*)	Associated grams CO_2 Emissions per kWh (*g/kWh*)	CO_2 emissions for space heating and hot water for each energy source (*kTCO*$_2$*/a*)
Gas			412.3	201.0	82.8
Fuel oil			344.8	275.8	95.1
Electricity	Nuclear	22%	14.0	19.7	0.3
	Natural gas	13%	8.3	201.0	1.7
	Lignite	23%	14.6	364.0	5.3
	Hard coal	19%	12.1	333.7	4.0
	Renewable energies	17%	10.8	0	0
	Other sources	6%	3.8		0
District heating			44.3	394.7	17.5
Coal			4.0	333.7	1.3
Wood			3.3	340	1.1
Solar			1.1	10	0.0114
		Total final energy consumption for space heating and hot water (*GWh/a*)	**873.5**	Total CO_2 emissions for space heating and hot water (*kTCO*$_2$*/a*)	**209.2**

Table 5
CO_2 emissions associated with a Heat Pump (CoP of 3.2).

Heat pump	*GWh/a* per electricity type	Assoc *gCO_2/kWh* per electricity type	Electricity type	Share provided by electricity type	*tCO_2/a* contributed by each electricity type
Electricity	60.0	19.70	Nuclear	22%	1.2
	35.5	200.95	Natural gas	13%	7.1
	62.8	364.03	Lignite	23%	22.9
	51.9	333.72	Hard coal	19%	17.3
	16.4		Other	6%	0
	46.4	0	Renewables	17%	0
				CO_2 emissions contributed by the heat pump with a CoP of 3.2 ($kTCO_2/a$)	**48.5**

4. Results and discussion

4.1. Heat energy demand

Table 1 shows the results of the calculation of the heat consumption values per settlement type (d_j), in kWh/m^2a, and the distribution of these settlement types is shown in Fig. 5.

The distribution of energy consumption shows the higher values corresponding to the centre of town where larger buildings, such as high rises and apartment blocks, are concentrated. The lower values are found further away from the centre, in the suburban areas where residential type buildings (single and double family houses, rural villages and terraced houses) are found. This can be seen in Fig. 6.

The results of the calculation of the energy demand for space heating and hot water per building (D_{ij}) are shown in Fig. 7.

The heat energy demand calculation per parcel yielded results within the expected ranges. The values calculated per settlement type versus those calculated per parcel differ because of how the energy consumption of the whole settlement type is distributed among all the smaller parcels within this type. Although the energy demand may not be that high, the parcel may remain unsuitable due to a lack of space, as for example on the more compact city settlement type parcels, for the installation of the required number of boreholes. More detailed information on the heat consumption per building type, rather than being inferred from settlement type (which gives an average consumption value per all buildings falling into each settlement type) would have resulted in more accurate heat consumption, and therefore heat energy demand values. At the time of developing this, there was no heat consumption data per building type available for Ludwigsburg.

These results are available on the Smart City Energy Platform (powered by iGuess [1]) for users to visualise the process. These are interactive layers where city planners and energy experts, such as energy agencies, can retrieve information and combine the different layers for further developments of more sustainable master plans and decide measures to reduce CO_2 emissions across the city with potential private public partnerships. The sampling layer is an example from the borehole optimisation algorithms to present a potential sampling design across the entire city. An example of the output can be seen in Fig. 8.

4.2. Geothermal potential energy

The specific heat extraction (sHE) is calculated using the maximum drilling depth allowed, as well as the rock types and the thickness of the layers. Fig. 9 shows the maximum drilling depths in Ludwigsburg, based on the presence of a deep groundwater aquifer that is protected and varies with the depth of this aquifer. The reason for the very shallow allowable drilling depths near the Neckar River is that the top of the aquifer is close to the surface at this location. Further away from the river, the maximum drilling depth increases, with the maximum allowable depth in the north east end of the district. The shallower drilling depths follow the course of the Neckar River and its tributaries.

The total specific heat extraction (sHE) potential of the subsurface down to the maximum drilling depth was calculated in a second step and the results are presented in Fig. 10. The areas with the highest potential correspond to areas where the maximum allowable drilling depth is deepest.

Therefore the north east of the city bears both the deepest drilling depth and the highest sHE potential. The lowest values are found along the course of the river where drilling is not possible, or not allowed.

The calculation of the specific heat extraction potential in Ludwigsburg was more accurate than previous studies, such as Ondreka's calculation [23] where an average sHE was used, not values specific to the rock types found, and a common drilling depth was used to calculate the sHE potential. Our method improved on this by taking rock type, layer thickness and maximum drilling depth into account when calculating the sHE potential. However, despite these improvements, the changes in sHE reflect the change in maximum allowable drilling depth rather than any major variations in the underlying geology because although the geological layers in the subsurface vary in thickness in different areas, the different rock types have similar specific heat extraction values (Table 3). Hence, due to the very homogeneous underground structure, the relationship between maximum drilling depth and specific heat extraction potential remains mostly linear. This would vary greatly in regions with more diverse rock types and complicated geological structure.

Table 6
Potential Reduction in CO_2 through the use of Geothermal Energy.

Total CO_2 emissions for space heating and hot water ($kTCO_2/a$)	209.2
Total CO_2 emissions for Ludwigsburg ($kTCO_2/a$) (2007)	539
Percentage of CO_2 emissions contributed by space heating and hot water	38.8%
CO_2 emissions contributed by the heat pump with a CoP of 3.2 ($kTCO_2/a$)	48.5
Percentage of CO_2 emissions contributed by a heat pump with a CoP of 3.2	8.9%
Potential percentage reduction of CO_2 emissions through using geothermal energy for space heating and hot water	**29.7%**

4.3. Demand satisfied by geothermal energy per parcel

The combination of the above parameters – heating energy demand per parcel, sHE per parcel and maximum number of boreholes per parcel – yielded the number and lengths of boreholes required to satisfy the heat energy demand per parcel and the percentage of this demand that can be satisfied by geothermal energy per parcel, which is shown in Fig. 11. The parcels which can have 100% of the energy demand for space heating and hot water satisfied by geothermal energy corresponds to 40% of the total parcels. These parcels appear to be mostly those of a more residential settlement type that have a lower energy demand and have enough space for the installation of the boreholes. These parcels are predominantly on the suburban parts of the city, where there are housing developments.

While 40% of parcels could theoretically have all the energy demand satisfied by geothermal energy, sometimes the number of boreholes required to do so is unrealistically high. Although the space may theoretically be available, a large number of boreholes installed on one parcel is not possible, as well as being extremely costly. Therefore, the fewer boreholes required to satisfy the energy demand the better. Fig. 11 shows those parcels requiring only one drilling in order to satisfy the energy demand. These parcels are residential in nature and represent 30.4% of the parcels.

For the calculation of the percentage of the demand that could be satisfied by geothermal energy, the assumption was made that all available space on parcels would be accessible by drilling rigs for the installation of bore-holes. This, however, would not be the case in reality as some available space would be unreachable from the road, for example. In future, further work could be done to this part of the methodology to take into account accessibility to available space via roads, driveways and ensuring openings would be big enough for drilling rigs.

4.4. Potential reduction in CO_2 emissions

The results of the calculation of the potential percentage reduction in CO_2 emissions through the use of geothermal energy for space heating and hot water are presented in Tables 4–6.

These values were calculated using the breakdown of energy consumption for space heating and hot water in Germany, as well as the associated grammes of CO_2 emissions for each energy carrier type. The amount of CO_2 emitted through energy consumed for space heating and hot water is $209.2kTCO_2/a$. This equates to 38.8% of the total CO_2 emissions for Ludwigsburg (for space heating and hot water). The amount of energy required to run a heat pump with a coefficient of performance (CoP) of 3.2 also needs to be taken into account. This amounts to 272.0 GWh/a, which results in 48.5 kT CO_2 or 8.9% of the total emissions.

Thus, the potential for reduction of CO_2 emissions by replacing all the current space heating and hot water requirements by geothermal energy, would be 29.7% (including the contribution by the heat pump). However, if we were to assume only those properties which could have 100% of the demand supplied by one borehole were switched to geothermal energy, the potential CO_2 emissions reduction would be 9.0%. This corresponds to 18.8 kT of CO_2 per year.

5. Conclusion

We conclude that the method developed in this study is a simple and useful tool for assessing the potential for utilising shallow geothermal energy for space heating and hot water. The method makes use of data which is easy to acquire and is of a higher resolution than previous studies. The results showed that there is a lower heating energy demand in the residential settlement types and these are more likely to be able to satisfy the energy demand for space heating and hot water through geothermal energy using only one borehole. Higher energy demand buildings corresponding to settlement types such as the city centre were less likely to have their energy demands satisfied by geothermal energy without requiring an unrealistic number of boreholes to do so. It follows then that the urban pattern should also be taken into consideration for future planning as the organisation of parcels and buildings impacts whether or not the required number (or a realistic number) of boreholes can be installed in order to satisfy the energy demand. From these results a less dense urban pattern would seem to be more suited to the use of shallow geothermal energy for space heating and hot water. Due to the availability of the results in the web-based platform Smart City Energy Platform solutions can be interactively explored with all stakeholders.

Acknowledgements

This work has been funded by the Luxembourg Institute of Science and Technology and the EU INTERREG IVB NWE Programme, Project 165F, the MUSIC Project.

References

[1] Luis de Sousa, Christopher Eykamp, Ulrich Leopold, Olivier Baume, Christian Braun, iGUESS – A web based system integrating urban energy planning and assessment modelling for multi-scale spatial decision making, in: Sixth Biennial Meeting. International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Leipzig, Germany, 2012. URL, http://www.iemss.org/sites/iemss2012/proceedings.html.
[2] 4640 Richtlinie VDI, Thermal Use of the Underground – Ground Source Heat Pump Systems, Beuth Verlag, 2004.
[3] N. Aydin, E. Kentel, S. Duzgun, GIS-based environmental assessment of wind energy systems for spatial planning: a case study from western Turkey, Renew. Sustain. Energy Rev. 14 (1) (Jan. 2010) 364–373. URL, http://linkinghub.elsevier.com/retrieve/pii/S1364032109001610.
[4] L. Bergamasco, P. Asinari, Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: further improvements by ortho-image analysis and application to Turin (Italy), Sol. Energy 85 (11) (Nov. 2011) 2741–2756. URL, http://linkinghub.elsevier.com/retrieve/pii/S0038092X11002830.
[5] M. Blesl, U. Fahl, A. Voss, Strategien und thechnologien einer pluralistischen fern- und nahwrme- versorgung in einem liberalisierten energiemarkt unter besonderer bercksichtigung der kraft-wrme- kopplung und regenerativer energien (pluralistische wrmeversorgung), 2011.
[6] G. Blewitt, M. Coolbaugh, W. Holt, C. Kreemer, J. Davis, R. Bennett, Targeting of potential geothermal resources in the great basin from regional relationship between geodetic strain and geological structures, Geotherm. Resour. Counc. Trans. 26 (2002) 523–526.
[7] P. Blum, G. Campillo, W. Mnch, T. Klbel, Co2 savings of ground source heat pump systems – a regional analysis, Renew. Energy 35 (1) (2010) 122–127.
[8] M. Brito, N. Gomes, T. Santos, J.A. Tenedório, Photovoltaic potential in a Lisbon suburb using LIDAR data, Sol. Energy 86 (1) (Jan. 2012) 283–288. URL, http://linkinghub.elsevier.com/retrieve/pii/S0038092X11003574.
[9] M. Coolbaugh, D. Sawatzky, G. Oppliger, T. Minor, G. Raines, L. Shevenelf, G. Blewitt, J. Louie, Geothermal GIS coverage of the great basin, USA: defining regional controls and favourable exploration terrains, Geotherm. Resour. Counc. Trans. 27 (Oct. 2003) 12–15.
[10] J. Dorfner, GIS-based mapping tool of urban energy demand for room heating and hot water, in: 17th Building Services, Mechanical and Building Industry Days, Debreen, Hungary, Oct. 2011.
[11] T. Dwyer, Y. Evans, Figure 1 : Approximate UK Annual Ground Temperatures, 2010. Online. URL, http://www.cibsejournal.com/cpd/2010-04/.
[12] European Commission, Europe 2020: A Strategy for Smart, Sustainable and Inclusive Growth. Brussels, 2010.
[13] U. Fahl, M. Sippel, M. Blesl, C. Kruck, M. Hrdtlein, L. Eltrop, R. Schelle, J. Lambauer, E. Heyden, C. Benighaus, A. Arnold, O. Renn, Integrated Climate Protection and Energy Strategy for Ludwigsburg – Summary of Key Findings, IER Stuttgart, DIALOGIK Stuttgart, City of Ludwigsburg, 2011.
[14] A. Gemelli, A. Mancini, S. Longhi, GIS-based energy-economic model of low temperature geothermal resources: a case study in the Italian Marche region, Renew. Energy 36 (9) (September 2011) 2474–2483.
[15] J. Janke, Multicriteria GIS modeling of wind and solar farms in Colorado, Renew. Energy 35 (10) (Oct. 2010) 2228–2234. URL, http://linkinghub.elsevier.com/retrieve/pii/S096014811000131X.
[16] A. Lashin, N. Al Arifi, Geothermal energy potential of southwestern of Saudi

Arabia exploration and possible power generation: a case study at Al Khouba area – Jizan, Renew. Sustain. Energy Rev. 30 (Feb. 2014) 771–789. URL, http://linkinghub.elsevier.com/retrieve/pii/S1364032113007363.
[17] T. Lovering, H. Goode, Measuring Geothermal Gradients in Drill Holes Less than 60 Feet Deep East Tintic District, Utah : Utilization of Shallow-hole Temperature Measurements in Finding Thermal Diffusivity and Conductivity of Rocks, Temperature Gradient, Average Surface Temperature, and Certain Kinds of Climatic Data, United States Government Printing Office, Washington, 1963.
[18] J. Lund, D. Freeston, T. Boyd, Direct utilization of geothermal energy 2010 worldwide review, Geothermics 40 (3) (Sep. 2011) 159–180. URL, http://linkinghub.elsevier.com/retrieve/pii/S0375650511000344.
[19] J. Lund, D. Freeston, T. Boyd, Direct utilization of geothermal energy 2010 worldwide review, Geothermics 40 (3) (September 2011) 159–180.
[20] A. Mastrucci, C. Braun, O. Baume, F. Stazi, U. Leopold, Towards a comprehensive approach to sustainable urban planning: integrated estimation of housing electricity consumption and photovoltaic generation potential using the web-based framework iGUESS, in: Renewable Energy in the Service of Mankind, vol. 1, Springer, 2015. URL, http://www.springer.com/us/book/9783319177762.
[21] J. Meester, Optimising Borehole Heat Exchanger Spacing to Maximise Advective Heat Transfer (Master's thesis), University of Minnesota, 2013. advisor: Martin O. Saar.
[22] Y. Noorollahi, R. Itoi, H. Fujii, T. Tanaka, GIS integration model for geothermal exploration and well siting, Geothermics 37 (2) (Apr. 2008) 107–131. URL, http://linkinghub.elsevier.com/retrieve/pii/S0375650507000995.
[23] J. Ondreka, M. Rüsgen, I. Stober, K. Czurda, GIS-supported mapping of shallow geothermal potential of representative areas in south-western Germany-possibilities and limitations, Renew. Energy 32 (13) (Oct. 2007) 2186–2200. URL, http://linkinghub.elsevier.com/retrieve/pii/S0960148106003338.
[24] T.V. Ramachandra, Solar energy potential assessment using GIS, Energy Educ. Sci. Technol. 18 (2) (2007) 101–114.
[25] B. Sanner, Overview of Shallow Geothermal Systems, Geotrainet, Brussels, 2011, pp. 1–13. Ch. 1.
[26] D. Sauer, R. Juraske, M. Kübert, P. Blum, S. Hellweg, P. Bayer, Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems, Renew. Sustain. Energy Rev. 14 (7) (Sep. 2010) 1796–1813. URL, http://linkinghub.elsevier.com/retrieve/pii/S1364032110001061.
[27] P. Steskens, Thermal Energy Storage in the Ground, February 2010, p. 3. Design Guide SET, figure 3.
[28] J.W. Tester, The Future Of Geothermal Energy – Impact Of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, Tech. rep., Idaho National Laboratory, US Department of Energy, 2006.
[29] D. Voivontas, G. Tsiligiridis, D. Assimacopoulos, Solar potential for water heating explored by GIS, Sol. Energy 62 (6) (Jun. 1998) 419–427. URL, http://linkinghub.elsevier.com/retrieve/pii/S0038092X98000279.
[30] World Commission and Development on Environment, Our Common Future, Oxford University Press, Oxford; New York, 1987.