Supplementary Materials: Suitability Evaluation of Specific Shallow Geothermal Technologies Using a GIS-Based Multi Criteria Decision Analysis Implementing the Analytic Hierarchic Process

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This supplementary material reports the main features, equations, references and data used in steps 1 to 6 of the GIS-based AHP-MCDA process.

Step 1

Data were collected from multiple open source databases of different kinds. All data were georeferenced. Geological open data were gathered from the EuroGeoSurveys' European Geological Data Infrastructure - EGDI web portal (www.europe-geology.eu). Hydrogeological information and bedrock data were taken respectively from the International Hydrogeological Map of Europe — IHME1500 [1] and the gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses [2]. Climate data were gathered from the Worldclim global climate database (www.worldclim.org), while geothermal heat flow data were collated from three existing public databases:

- The global heat flow database of the International Heat Flow Commission (IHFC, www.geophysik.rwth-aachen.de/IHFC);
- The database obtained from the atlas of geothermal resources in Europe [3];
- The database obtained from the book of Terrestrial Heat Flow in Europe [4].

The Global Land Cover map was obtained from the European Space Agency GlobCover Portal [5], the Population Density map from Gridded Population of the World, V4", Center for International Earth Science Information Network, Columbia University, 2016 (http://sedac.ciesin.columbia.edu).

Finally, a new internal database of rock and soil thermal and mechanical properties (each property reported as a probability distribution) was created, based on significant bibliography [6–12] Contents of the database are divided in Tables S1–S5 and presented below.

Table S1. Range of compressive strength of rocks (MPa).

Extremely Hard	Very Hard	Hard	Medium	Soft	Very Soft	Extremely Soft
> 250.00	100.00 250.00	50.00 100.00	25.00 50.00	5.00 25.00	1.00 5.00	0.25 1.00
Basalt	Amphibolite	Limestone	Claystone	Chalk	Highly weathered or altered rock	Stiff fault gauge
Diabase	Sandstone	Marble	Coal	Rocksalt		
Gneiss	Basalt	Phyllite	Concrete	Potash		
Quartzite	Gabbro	Sandstone	Schist			
Diabase	Granodiorite	Schist	Shale			
	Limestone	Shale	Siltstone			
	Marble					
	Tuff					
	Rhyolite					

Table S2. Range of shear strength of unconsolidated material, with groundwater presence (MPa).

Sediment Type	Minimum	Maximum	Average	Standard Deviation
Very soft clay	0.16	0.29	0.2291	0.0654
Soft clay	0.27	0.39	0.3277	0.0600
Firm clay	0.43	0.62	0.5226	0.0968
Stiff clay	0.78	0.78	0.7756	0.0000
Hard clay	1.46	1.56	1.5088	0.0466
Silt	0.35	0.44	0.3974	0.0471
Dense dry gravel	0.47	1.04	0.7551	0.2890
Dense sand	0.34	0.49	0.4186	0.0745
Weak sand	0.23	0.35	0.2874	0.0582
Clastic sediment	0.16	1.56	0.8596	0.6959

Table S3. Range of shear strength of dry sediments and rocks (MPa).

Sediment and Rock Type	Minimum	Maximum	Average	Standard Deviation
Very soft clay	0.02	0.03	0.03	0.01
Soft clay	0.11	0.13	0.12	0.01
Firm clay	0.27	0.31	0.29	0.02
Stiff clay	0.55	0.81	0.68	0.13
Hard clay	1.23	1.33	1.28	0.05
Silt	0.10	0.10	0.10	0.00
Dense dry gravel	0.13	0.70	0.42	0.28
Dense sand	0.00	0.00	0.00	0.00
Weak sand	0.00	0.00	0.00	0.00
Peat	0.00	0.00	0.00	0.00
Extremely soft rock	0.13	0.75	0.44	0.31
Very soft rock	0.48	3.55	2.01	1.54
Soft rock	2.43	17.71	10.07	7.64
Medium rock	11.86	35.31	23.58	11.73
Hard rock	23.62	70.42	47.02	23.40
Very hard rock	47.03	176.05	111.54	64.51
Extremely hard rock	117.58	351.10	234.34	116.76
Anhydrite	55.96	84.02	69.99	14.03
Marl	0.28	6.73	3.50	3.23
Coal	12.70	20.61	16.66	3.96
Claystone	0.59	6.31	3.45	2.86
Conglomerate	21.21	91.33	56.27	35.06
Chalk	1.83	12.90	7.37	5.53
Dolomite	11.95	211.06	111.50	99.56
Limestone	15.69	189.39	102.54	86.85
Mudstone	2.51	84.02	43.26	40.75
Shale	2.85	88.04	45.44	42.60
Sandstone	10.05	125.74	67.90	57.84
Siltstone	5.30	117.19	61.24	55.95
Tuff	73.56	251.00	162.28	88.72

Andesite	34.97	210.06	122.52	87.54
Anorthosite	18.65	147.04	82.85	64.20
Basalt	38.22	320.64	179.43	141.21
Diabase (dolerite)	62.89	255.29	159.09	96.20
Diorite	49.17	97.81	73.49	24.32
Gabbro	89.00	200.56	144.78	55.78
Granite	95.40	520.62	308.01	212.61
Graonodiorite	83.82	250.93	167.37	83.55
Monzonite	40.04	162.05	101.04	61.01
Nepheline Syenite	26.97	47.17	37.07	10.10
Norite	290.00	564.65	427.32	137.32
Pegmatite	39.00	107.39	73.19	34.19
Rhyolite	27.98	105.03	66.50	38.53
Syenite	21.06	55.60	38.33	17.27
Basalt	48.47	282.26	165.37	116.90
Amphibolite	47.27	156.22	101.74	54.48
Amphibolitic gneiss	40.33	127.49	83.91	43.58
Augen gneiss	40.73	128.49	84.61	43.88
Garnet mica schist	0.00	0.00	0.00	0.00
Granite gneiss	10.92	81.63	46.28	35.36
Gneiss	34.36	86.92	60.64	26.28
Gneiss granite	0.00	0.00	0.00	0.00
Greenschist	34.36	103.55	68.95	34.59
Greywacke	36.43	99.03	67.73	31.30
Marble	14.73	53.51	34.12	19.39
Mica gneiss	0.00	0.00	0.00	0.00
Mica quartzite	93.65	141.02	117.34	23.69
Mica schist	35.41	275.10	155.26	119.85
Phyllite	23.75	86.36	55.05	31.31
Quartz sandstone	38.16	126.00	82.08	43.92
Quartzite	12.80	106.63	59.71	46.92
Quartzitic phyllite	0.00	0.00	0.00	0.00
Serpentinite	2.32	87.60	44.96	42.64
Slate	51.26	137.72	94.49	43.23
Talc schist	63.33	246.00	154.67	91.33
Rhyolite	17.67	90.49	54.08	36.41
Phonolite	37.93	146.31	92.12	54.19
Syenite	5.86	86.80	46.33	40.47
Tephrite	28.42	56.64	42.53	14.11
Trachyte	45.16	55.60	50.38	5.22
Travertine	48.61	59.24	53.92	5.31
Evaporite	27.95	59.24	43.59	15.64
Rock salt	27.95	37.40	32.67	4.73
Gypsum	48.61	59.24	53.92	5.31
Anhydrite	10.59	65.05	37.82	27.23
Flint	111.50	369.06	240.28	128.78
Pozzolana	12.95	32.37	22.66	9.71

Monzogranite	27.23	60.25	43.74	16.51
Hornfels	111.50	261.83	186.66	75.17
Porphyry	231.34	289.68	260.51	29.17

Table S4. Range of thermal conductivity of sediments and rocks (W/(m·K)).

Sediment and Rock Type	Minimum	Maximum	Average	Standard Deviation
Dry clay	0.40	1.00	0.70	0.30
Wet clay	0.90	2.30	1.60	0.70
Dry silt	0.40	1.00	0.70	0.30
Wet silt	0.90	2.30	1.60	0.70
Dry gravel	0.40	0.50	0.45	0.05
Wet gravel	1.00	1.80	1.40	0.40
Dry sand	0.30	0.80	0.55	0.25
Wet sand	1.70	5.00	3.35	1.65
Peat	0.20	0.70	0.45	0.25
Claystone	1.10	3.40	2.25	1.15
Siltstone	1.10	3.40	2.25	1.15
Mudstone	1.10	3.40	2.25	1.15
Sandstone	1.90	4.60	3.25	1.35
Limestone	2.00	3.90	2.95	0.95
Shale	1.50	3.10	2.30	0.80
Basalt	1.30	2.30	1.80	0.50
Diorite	2.00	2.90	2.45	0.45
Gabbro	1.70	2.50	2.10	0.40
Granite	2.10	4.10	3.10	1.00
Peridotite	3.80	5.90	4.85	1.05
Rhyolite	3.10	3.40	3.25	0.15
Gneiss	1.90	4.00	2.95	1.05
Marble	1.30	3.10	2.20	0.90
Mica schist	1.50	3.10	2.30	0.80
Schist	1.50	2.60	2.05	0.55
Quartzite	3.60	6.60	5.10	1.50
Breccia	1.30	5.10	3.20	1.90
Tuff	0.94	2.10	1.52	0.58
Dolomite	2.50	5.30	3.90	1.40
Evaporite	5.00	5.50	5.25	0.25
Gypsum	0.40	0.40	0.40	0.00
Phyllite	2.70	3.80	3.25	0.55
Marl	1.50	2.00	1.75	0.25
Anthracite	2.10	2.10	2.10	0.00
Granodiorite	2.05	3.50	2.78	0.73
Migmatite	2.10	4.10	3.10	1.00
Phonolite	3.10	3.40	3.25	0.15
Andesite	2.00	2.90	2.45	0.45
Conglomerate	1.30	5.10	3.20	1.90
Bauxite	2.50	5.00	3.75	1.25
Tonalite	2.30	2.60	2.45	0.15
Travertine	1.30	1.90	1.60	0.30
Flint	0.50	0.70	0.60	0.10
Latite	3.10	3.40	3.25	0.15
Trachite	3.10	3.40	3.25	0.15

Serpentine	3.80	5.90	4.85	1.05
Syenite	3.10	3.40	3.25	0.15
Coal	2.10	2.10	2.10	0.00
Amphibolite	2.10	4.10	3.10	1.00
Granulite	2.10	4.10	3.10	1.00
Eclogite	1.30	2.30	1.80	0.50
Slate	0.45	0.55	0.50	0.05
Lignite	2.10	2.10	2.10	0.00
Chalk	0.82	1.02	0.92	0.10
Halite	4.50	5.50	5.00	0.50
Hornfels	2.35	3.45	2.90	0.55
Porphyry	2.70	3.50	2.90	0.40
Pegmatite	2.79	3.61	3.20	0.41
Syenogranite	2.10	4.10	3.10	1.00
Foid dioritoid	0.40	1.00	0.70	0.30

Table S5. Range of thermal diffusivity of sediments and rocks (m^2/days)

Sediment and Rock Type	Minimum	Maximum	Average	Standard Deviation
Dry clay	0.02	0.05	0.04	0.02
Wet clay	0.04	0.07	0.05	0.02
Dry silt	0.02	0.05	0.04	0.02
Wet silt	0.04	0.07	0.05	0.02
Dry gravel	0.03	0.03	0.03	0.00
Wet gravel	0.04	0.06	0.05	0.01
Dry sand	0.02	0.04	0.03	0.01
Wet sand	0.07	0.15	0.11	0.04
Peat	0.03	0.02	0.03	0.01
Claystone	0.05	0.12	0.08	0.04
Siltstone	0.05	0.12	0.08	0.04
Mudstone	0.05	0.12	0.08	0.04
Sandstone	0.09	0.15	0.12	0.03
Limestone	0.08	0.14	0.11	0.03
Shale	0.06	0.11	0.09	0.03
Basalt	0.05	0.08	0.06	0.01
Diorite	0.06	0.09	0.07	0.01
Gabbro	0.06	0.08	0.07	0.01
Granite	0.09	0.12	0.10	0.02
Peridotite	0.12	0.19	0.16	0.03
Rhyolite	0.13	0.14	0.13	0.01
Gneiss	0.09	0.14	0.12	0.03
Marble	0.06	0.13	0.10	0.04
Mica schist	0.06	0.12	0.09	0.03
Schist	0.06	0.09	0.07	0.02
Quartzite	0.15	0.27	0.21	0.06
Breccia	0.05	0.18	0.12	0.07
Tuff	0.41	0.50	0.46	0.05
Dolomite	0.14	0.31	0.22	0.08
Evaporite	0.19	0.20	0.20	0.01
Gypsum	0.01	0.01	0.01	0.00
Phyllite	0.13	0.12	0.13	0.00

Marl	0.06	0.07	0.07	0.00
Anthracite	0.10	0.10	0.10	0.00
Granodiorite	0.09	0.16	0.13	0.03
Migmatite	0.11	0.17	0.14	0.03
Phonolite	0.13	0.14	0.13	0.01
Andesite	0.06	0.09	0.07	0.01
Conglomerate	0.05	0.18	0.12	0.07
Bauxite	0.10	0.21	0.15	0.05
Tonalite	0.08	0.09	0.08	0.00
Travertine	0.05	0.05	0.05	0.00
Flint	0.02	0.03	0.02	0.00
Latite	0.13	0.14	0.13	0.01
Trachite	0.13	0.14	0.13	0.01
Serpentine	0.12	0.19	0.16	0.03
Syenite	0.13	0.14	0.13	0.01
Coal	0.12	0.08	0.10	0.02
Amphibolite	0.09	0.12	0.10	0.02
Granulite	0.09	0.12	0.10	0.02
Eclogite	0.05	0.08	0.06	0.01
Slate	0.02	0.02	0.02	0.00
Lignite	0.14	0.14	0.14	0.00
Chalk	0.04	0.05	0.05	0.00
Halite (Rock salt)	0.31	0.24	0.27	0.04
Hornfels	0.09	0.12	0.10	0.01
Porphyry	0.11	0.11	0.11	0.00
Pegmatite	0.14	0.17	0.15	0.01
Syenogranite	0.09	0.14	0.11	0.03
Foid dioritoid	2.00	2.90	2.45	0.45

Step 2

No geological, hydrogeological and geothermal heat flow data were found for some areas in several countries. This information shortfall was managed in the mapping process using geostatistical estimation [13].

Kriging and Co-Kriging geostatistical techniques were used to estimate missing data and check data quality, by validation at different scales of work given the intrinsic uncertainty of the initial data.

The degree of the spatial uniformity was evaluated by declustering [14]. Based on moving windows, the declustering method computes the weight w_i attached to a target sample i, by counting the number n_i of samples inside the moving window centred on this target sample.

The weight w_i is then the result of the division between the mean m_v of data inside a window and the number of data n_i.

$$w_i = \frac{m_v}{n_i} \quad \text{S(1)}$$

As the spatial variability structure of the data, obtained by variogram analysis, shows strong and evident correlations between two or more interest variables (correlations between variables dealing with climate, between different ground thermal properties, and between ground thermal and geomechanical properties), the Co-Kriging (CK) interpolation method was therefore considered able to improve the quality of shallow geothermal energy potential maps.

Experimental variograms and cross-variograms were used to quantify the spatial variability. The generalized form of the variogram, using the auxiliary variable, is expressed as:

$$\gamma_{ij}(h)=\frac{1}{2}\cdot E\left[Z_i(x+h)-Z_i(x)\right]\cdot\left[Z_j(x+h)-Z_j(x)\right] \qquad \text{S(2)}$$

where γ_{ij}(h) is the cross-variogram, Z_i(x) is the target variable at the coordinate *x*, Z_j(x) is the auxiliary variable at the coordinate *x* and *h* is the distance between pairs.

The CK estimator for evaluation of the target variable Z_i at the *x* coordinate, when adding the auxiliary variable Z_j, is expressed by:

$$Z_i^*(x)=\sum_{\alpha}\nu_{i\alpha}\cdot Z_i(x_\alpha)+\sum_{\alpha}\nu_{j\alpha}\cdot Z_j(x_\alpha) \qquad \text{S(3)}$$

where $\nu_{i\alpha}$ and $\nu_{j\alpha}$ are the weights of the linear interpolation; they are the result of the CK system presented below:

$$\begin{cases}\sum_{\beta\in S_i}\nu_{i\beta}\cdot\gamma\left(Z_{i\alpha},Z_{i\beta}\right)+\sum_{\beta\in S_2}\nu_{j\beta}\cdot\gamma\left(Z_{i\alpha},Z_{j\beta}\right)+\mu_i=\gamma\left(Z_{i0},Z_{i\alpha}\right)\\ \sum_{\beta\in S_j}\nu_{i\beta}\cdot\gamma\left(Z_{i\beta},Z_{j\alpha}\right)+\sum_{\beta\in S_2}\nu_{j\beta}\cdot\gamma\left(Z_{j\alpha},Z_{j\beta}\right)+\mu_j=\gamma\left(Z_{i0},Z_{j\alpha}\right)\\ \sum_{\alpha\in S_i}\nu_{i\alpha}=1\\ \sum_{\alpha\in S_j}\nu_{j\alpha}=0\end{cases} \qquad \text{S(4)}$$

where μ_i and μ_j are the Lagrange multipliers introduced to insert the conditions on weights ν in the system.

The variogram models for the target variable γ_i and the auxiliary variable γ_j, and the cross-variogram model between the two variables γ_{ij} are also included in the system.

Geostatistical analysis has the additional benefit of producing variances and covariances of estimated variables for each point of the grid

$$\sigma_i^2=\sum_{\alpha\in S_i}\nu_\alpha\cdot\gamma\left(Z_{i0},Z_{i\alpha}\right)+\sum_{\beta\in S_j}\nu_\beta\cdot\gamma\left(Z_{i0},Z_{j\beta}\right)+\mu_i \qquad \text{S(5)}$$

$$\sigma_{i,j}=-\sum_i\sum_j\sum_{\alpha\in S_i}\sum_{\beta\in S_j}\nu_\alpha\cdot\bar{\nu}_\beta\cdot\gamma\left(Z_{i\alpha},Z_{j\beta}\right) \qquad \text{S(6)}$$

In the shallow geothermal analysis of the present work, the estimated variables were not the final target. Once all available information was collected on a mapping scale, the analytical models were adopted to calculate the specific target.

The estimation variances and covariances for each variable (and couple of interrelated variables) were then upgraded to the final target. This was done through propagation of uncertainty techniques.

Step 3

Innovative GEOTeCH technologies are currently in the validation phase by the GEOTeCH Consortium. It follows that the technical specifications used in this work concern the preliminary results based on prototypes and field tests. No specific data regarding the GEOTeCH technological advances can be published at the time of present paper.

Step 4

Drillability index was calculated starting from the Coulomb Law of Failure [15] adapted to calculating the cutting potential of drilling bits [16].

$$\tau(x,y,d)=c+\left[\sigma_v+p(d)\right]\cdot\tan\varphi \qquad \text{S(7)}$$

In the above equation, c is the cohesion (MPa), σ_v is the compressive strength (MPa), p is the hydrostatic pressure (MPa), d is the depth (m) and φ is the friction angle.

The wide variability of geological and geomechanical properties made setting a typical average shear strength value for each type of rock very difficult. In the absence of detailed information, an interval of uncertainty was considered in order to account for the probability behaviour of geomechanical data. This is particularly impactful for the potential application of hollow stem auger in soft rocks.

All the lithotypes from geological maps were taken into account by calculating the shear strength as a weighted average, giving more impact to the predominant lithotypes as classified by the National Geological Surveys (EGDI portal). The Gaussian distribution was used to represent the shear strength value for each lithotype since its natural range is known from bibliographic information.

Hydrogeology impacts the calculation of the shear strength for unconsolidated materials. The distribution of shear strength values was modified in accordance with the information gathered on the type of aquifer and the presence of hydrostatic pressure.

Bedrock depth impacts the weighted average between geological layers. Bedrock depth adds rock strength values depending on the geological stratigraphy. The proportion between bedrock depth and total depth of investigation was calculated on a logarithmic scale, assigning greater importance to the shallowest layers, which most influence the feasibility of drilling for hollow stem auger.

The following comprehensive weighted average was applied.

$$\tau(x,y)=\frac{\sum_{i=1}^{n}(\omega_{si}\cdot\tau_{si})\cdot\left(\frac{\log_{10}(d_b)}{\log_{10}(d)}\right)+\sum_{i=1}^{n}(\omega_{bi}\cdot\tau_{bi})\cdot\left[\frac{\log_{10}\left(\frac{d}{d_b}\right)}{\log_{10}(d)}\right]}{n} \qquad \text{S(8)}$$

where τ(x,y) is the resulting value of shear stress for the selected coordinate (MPa), n is the number of layers, τ_{si} are the shear strength of sediment layers and ω_{si} their weights, τ_{bi} are the shear strength of bedrock layers and ω_{bi} their weights, d is the investigation depth (in this work set at 50 m) and d_b is the depth of bedrock (m).

The incertitude of shear strength for each geological layer had to be propagated to the final value, filling the grid node.

The equation used to calculate the regionalized weighted standard deviation S is:

$$S=\sqrt{\frac{\sum_{i}^{nl}s_i^2\cdot w_i+\sum_{i}^{nl}w_i\cdot(m_i-M)^2}{\sum_{i}^{nl}w_i}} \qquad \text{S(9)}$$

where σ^2_i is the shear strength variance associated to each geological sediment or lithotype, including groundwater presence; m_i is the shear strength average value associated to each geological sediment or lithotype, including groundwater presence; w_i is the regionalized weight indicating the approximated thickness percentage of different layers, up to 50 m, considering the information available on sediment thicknesses; M is the regionalized weighted average value of shear strength; n_l is the number of layers for each grid node, as stated in the official country geological maps of EGDI and IGME5000.

The final shear strength value, together with its uncertainty, was used to identify a drillability index for the specific area. It took into account geology, geomechanical properties of soils and rocks, hydrogeology and estimated thickness of sediments for each investigated zone.

The drillability index was the result of a risk assessment based on a threshold and assumes values from 0 (null probability of easy drilling with hollow stem auger) to 1 (full probability of easy drilling with hollow stem auger, up to the desired depth)

A shear strength threshold of 15 MPa was taken as the threshold for the use of hollow stem auger in unconsolidated material and soft rocks [17].

Geostatistical results match risk assessment very well, since each point presents an estimated value with a standard deviation. Once the threshold and the distribution function (supposed Gaussian) was defined, the probability of exceeding the threshold was calculated.

An in-house VBA® programme was developed to calculate the drillability index for each point of the grid for all European countries.

Step 5

Ground temperature evolution was calculated using the analytical equation of temperature distribution in the ground [18], modified according to recent research on subsurface urban heat island (SUHI) inclusion [19]. Correlations among Global Land Cover, Population Density and ground temperature were found to include SUHI in the calculation.

The basic equation for assessing the variation of the vertical temperature distribution (T_g) over time is generically a function of the ambient temperature wave, the thermal properties of the ground layers and the geothermal gradient [20]. Since all the variables entering the function are regionalized, the target variable is four dimensional, varying in space and time. The following equation summarizes the well-known temperature distribution in the subsoil:

$$T(x,y,d,t) = T_m - A\cdot\exp\left[-d\cdot\sqrt{\left(\frac{\pi}{365\cdot\alpha}\right)}\right]\cdot\cos\left[\frac{2\cdot\pi}{365}\cdot\left(t - t_{T_0} - \frac{d}{2}\cdot\sqrt{\frac{365}{\pi\cdot\alpha}}\right)\right] + \nabla\vec{T}\cdot d \quad \text{S(10)}$$

where T_m is the annual surface average temperature at location XY (°C), A is the wave amplitude at location XY (°C), the year is the wave period, d is depth (m), t is time (days), t_{T0} is the time at minimum temperature (days), α is the equivalent thermal diffusivity on the depth of investigation (m^2/days) and $\nabla\vec{T}$ is the geothermal gradient at location XY (°C/m), depending on geothermal heat flow HF (W/m^2) and equivalent thermal conductivity on the depth of investigation λ (W/(m·K)):

$$\nabla\vec{T} = \frac{h_f}{\lambda} \quad \text{S(11)}$$

Recent studies improved the calculation of T_m, A and t_{T0}, starting from climate information. The different surface heat flux contributions should be considered [21]; these are:

- the conduction heat flux into the ground;
- the convective heat flux transferred between ground surface and ambient air;
- the radiant flux absorbed by the ground surface;
- the radiant flux exchanged by the surroundings;
- the latent heat flux of evaporation.

Next equation reports a simplified calculation of average surface temperature T_m starting only from the ambient average temperature T_{amb}, which proved to be the predominant factor [22]:

$$T_m = 17.898 + 0.95\cdot T_{amb} \quad \text{S(12)}$$

where T_m and T_{amb} are expressed in Kelvin.

The replacement of the natural soil and vegetation by artificial surfaces increases the air and subsurface temperature around a building throughout the year, due to: indirect solar heating by urban structures, building heat losses and land-use change. At a district or city level, this phenomenon is called Urban Heat Island effect [23].

Several experimental studies have demonstrated that the heat loss from buildings increases the subsurface temperature by several degrees and this thermal impact is more persistent in the subsurface than in the air because of slower heat transfer underground [24].

Therefore, the contribution of SUHI was taken into account, too. Its contribution was related to global land cover and population density, with regression analysis, calculated from data taken from relevant literature [25–34].

The estimation variances of different variables had to be propagated. The uncertainty of the final target, the subsoil temperature T, was expressed by:

$$\sigma_T^2 = \left(\frac{\partial T}{\partial \alpha}\right)^2 \cdot \sigma_\alpha^2 + \left(\frac{\partial T}{\partial \lambda}\right)^2 \cdot \sigma_\lambda^2 + 2 \cdot \left(\frac{\partial T}{\partial \alpha}\right) \cdot \left(\frac{\partial T}{\partial \lambda}\right) \cdot \sigma_{\alpha,\lambda} + \\ + \left(\frac{\partial T}{\partial T_m}\right)^2 \cdot \sigma_{T_m}^2 + \left(\frac{\partial T}{\partial A}\right)^2 \cdot \sigma_A^2 + 2 \cdot \left(\frac{\partial T}{\partial T_m}\right) \cdot \left(\frac{\partial T}{\partial A}\right) \cdot \sigma_{T_m,A} + \left(\frac{\partial T}{\partial h_f}\right)^2 \cdot \sigma_{h_f}^2 \quad \text{S(13)}$$

The couples of variables α and λ, and T_m and A showed a clear interrelation when making the structural analysis, so estimation covariances were added to the equation.

A correct understanding of subsoil temperature distribution is important in a shallow geothermal energy (SGE) field and overall when dealing with short BHEs. The correct definition of the *neutral zone* (*NZ*) boundaries, where temperature is constant over space and time, can help to assess the geothermal potential of each project. The depth of the *NZ* is usually found between 10 and 20 m depth and is of variable thickness. Depth and thickness of neutral zone change with the geological, geothermal and climate characteristics of the surveyed area

A three-dimensional reconstruction of subsoil temperatures allowed quantification of the neutral zone layer boundaries (Z_{top} and Z_{bottom}) through appropriate goal-seek functions. The goal-seek function to find Z_{top} and Z_{bottom} was based on calculation of temperature time-mean and time-variance along the depth of investigation for each *XY* coordinate of the grid.

Step 6

The appropriate energy demand was calculated just for heating and cooling of small residential buildings (100–200 m^2), since this is the main target of the GEOTeCH dual source heat pump. The approach followed the standard application of Degree Days, representing the difference between room comfort temperature (set at 20°C) and outdoor ambient temperature, varying along the year (www.degreedays.net).

References

1. BGR & UNESCO (Eds.) *International Hydrogeological Map of Europe 1:1,500,000 (IHME1500)*; Digital Map Data v1.1. 2014. Available online: https://produktcenter.bgr.de (accessed on 15 October 2016).
2. Pelletier, J.D.; Broxton, P.D.; Hazenberg, P.; Zeng, X.; Troch, P.A.; Niu, G.-Y.; Williams, Z.; Brunke, M.A.; Gochis, D. A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modelling. *J. Adv. Model. Earth Syst.* **2016**, *8*, 41–65, doi:10.1002/2015MS000526.
3. Hurter, S.; Haenel, R. *Atlas of Geothermal Resources in Europe*; Leibniz Institute for Applied Geosciences (GGA): Hannover, Germany, 2002.
4. Cermak, V.; Rybach, L. *Terrestrial Heat Flow in Europe*; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 1979; ISBN 10:3540094407; 13:9783540094401.
5. Arino, O.; Bontemps, S.; Defourny, P.; Kalogirou, V.; Ramos Perez, J.; Van Bogaert, E.; Weber, J. *Pan-European Land Cover/Use Map for 2009*; PANGAEA: Hong Kong, China, 2010; doi:10.1594/PANGAEA.778363.
6. Clark, S.P., Jr. *Handbook of Physical Constants*; Geological Society of America: Boulder, CO, USA, 1966; doi:10.1130/MEM97.

7. Jaeger, J.C.; Cook, N.G.W. *Fundamentals of Rock Mechanics*; Chapman and Hall: London, UK, 1979; ISBN 041222010.
8. Beniawski, Z.T. *Engineering Rock Mass Classification. A Complete Manual for Engineers and Geologists in Mining, Civil and Petroleum Engineering*; John Wiley and Sons: Hoboken, NJ, USA, 1989; ISBN 0471601721.
9. Palmstrøm, A. Characterizing rock masses by the RMi for use in practical rock engineering: Part 1: The development of the Rock Mass index (RMi). *Tunn. Undergr. Space Technol.* **1996**, *11*, 175–188.
10. Robertson, E.C. *Thermal Properties of Rocks*; United States Department of the Interior—Geological Survey: Reston, VA, USA, 1988.
11. Ahrens, T.J. *Rock Physics & Phase Relations: A Handbook of Physical Constants*; American Geophysical Union: Washington, DC, USA, 1995; doi:10.1029/RF003.
12. Cermak, V.; Rybach, L. Thermal properties: Thermal conductivity and specific heat of minerals and rocks. In *Landolt-Bornstein Zahlenwerte and Funktionen aus Naturwissenschaften und Technik, Neue Serie, Physickalische Eigenshaften der Gesteine*; Angeneister, G., Ed.; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 1982; Volume V/1a, pp. 305–343.
13. Matheron, G. *The Theory of Regionalized Variables and Its Application*; Mathematical Statistics; École Nationale Supérieure des Mines de Paris: Paris, France, 1971; 211p.
14. Pyrcz, M.J.; Deutsch, C.V. Declustering and Debiasing; Available online: http://gaa.org.au/pdf/DeclusterDebias-CCG.pdf (accessed on 15 October 2016).
15. Coulomb, C.A. *Essai sur une Application des Regles des Maximis et Minimis a Quelquels Problemes de Statique Relatifs a la Architecture*; De l'Imprimerie Royale: Paris, France, 1776; Volume 7, pp. 343–387.
16. Bourgoyne, A.T.; Chenevert, M.E.; Millheim, K.K.; Young, F.S., Jr. *Applied Drilling Engineering*; SPE Textbook Series; Society of Petroleum Engineers: Richardson, TX, USA, 1986; Volume 2, ISBN 1555630014.
17. Bieniawski, Z.T. *Engineering Rock Mass Classifications*; Wiley: New York, NY, USA, 1989.
18. Kusuda, T.; Achenbach, P.S. Earth Temperature and Thermal Diffusivity at Selected Stations in the United States. Available online: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0472916 (accessed on 15 October 2016).
19. Bayer, P.; Rivera, J.A.; Schweizer, D.; Schärli, U.; Blum, P.; Rybach, L. Extracting past atmospheric warming and urban heating effects from borehole temperature profiles. *Geothermics* **2016**, *64*, 289–299, doi:10.1016/j.geothermics.2016.06.011.
20. Baggs, S.A. Remote prediction of ground temperature in Australian soils and mapping its distribution. *Sol. Energy* **1983**, *30*, 351–366, doi:10.1016/0038-092X(83)90189-5.
21. Ouzzane, M.; Eslami-Nejad, P.; Badache, M.; Aidoun, Z. New correlations for the prediction of the undisturbed ground temperature. *Geothermics* **2015**, *53*, 379–384, doi:10.1016/j.geothermics.2014.08.001.
22. Badache, M.; Eslami-Nejad, P.; Ouzzane, M.; Aidoun, Z.; Lamarche, L. A new modeling approach for improved ground temperature profile determination. *Renew. Energy* **2016**, *85*, 436–444, doi:10.1016/j.renene.2015.06.020.
23. Bornstein, R.D. Observation of the Urban Heat Island effect in New York City. *J. Appl. Meteorol.* **1968**, *7*, 575–581.
24. Landsberg, H.E. *The Urban Climate*. Academic Press: Cambridge, MA, USA, 1981.
25. Allen, A.; Milenic, D.; Sikora, P. Shallow gravel aquifers and the urban 'heat island' effect: A source of low enthalpy geothermal energy. *Geothermics* **2003**, *32*, 569–578.
26. Arola, T.; Korkka-Niemi, K. The effect of urban heat islands on geothermal potential: Examples from Quaternary aquifers in Finland. *Hydrogeol. J.* **2014**, *22*, 1953–1967, doi:10.1007/s10040-014-1174-5.
27. Ferguson, G.; Woodbury, A.D. Subsurface heat flow in an urban environment. *J. Geophys. Res.* **2004**, *109*, doi:10.1029/2007GL032324.
28. Ferguson, G.; Woodbury, A.D. Urban heat island in the subsurface. *Geophys. Res. Lett.* **2007**, *34*, 4, doi:10.1029/2007GL032324.
29. Headon, J.; Banks, D.; Waters, A.; Robinson, V.K. Regional distribution of ground temperature in the Chalk aquifer of London UK. *Q. J. Eng. Geol. Hydrogeol.* **2009**, *42*, 313–323, doi:10.1144/1470-9236/08-073.
30. Huang, S.; Taniguchi, M.; Yamano, M.; Wang, C.H. Detecting urbanization effects on surface and subsurface thermal environment—A case study of Osaka. *Sci. Total Environ.* **2009**, *407*, 3142–3152, doi:10.1016/j.scitotenv.2008.04.019.

31. Menberg, K.; Bayer, P.; Zosseder, K.; Rumohr, S.; Blum, P. Subsurface urban heat islands in German cities. *Sci. Total Environ.* **2013**, *442*, 123–133, doi:10.1016/j.scitotenv.2012.10.043.
32. Taniguchi, M.; Uemura, T.; Jago-on, K. Combined effects of urbanization and global warming on subsurface temperature in four Asian cities. *Vadose Zone J.* **2007**, *6*, 591–596, doi:10.2136/vzj2006.0094.
33. Yalcin, T.; Yetemen, O. Local warming of groundwaters caused by the urban heat island effect in Istanbul, Turkey. *Hydrogeol. J.* **2009**, *17*, 1247–1255, doi:10.1007/s10040-009-0474-7.
34. Zhu, K.; Blum, P.; Ferguson, G.; Balke, K.-D.; Bayer, P. The geothermal potential of urban heat islands. *Environ. Res. Lett.* **2010**, *5*, doi:10.1088/1748-9326/6/1/019501.