Governance of shallow geothermal energy resources

Alejandro García-Gil[1] *, Gregor Goetzl[2], Maciej R. Kłonowski[3], Staša Borovic[4], David P. Boon[5], Corinna Abesser[6], Mitja Janza[7], Ignasi Herms[8], Estelle Petitclerc[9], Mikael Erlström[10], Jan Holecek[11], Taly Hunter[12], Vincent P. Vandeweijer[13], Radovan Cernak[14], Miguel Mejías Moreno[1] and Jannis Epting[15]

[1] Geological Survey of Spain (IGME), C/ Ríos Rosas 23, 28003 Madrid, Spain.

[2] Geological Survey of Austria (GBA), Neulinggasse 38, 1030, Wien, Austria.

[3] Polish Geological Institute (PIG-PIB), Lower Silesian Branch, 19 Jaworowa St., 53-122 Wrocław, Poland.

[4] Croatian Geological Survey (HGI-CGS), Sachsova 2, 10000 Zagreb, Croatia.

[5] British Geological Survey (BGS-UKRI), Keyworth, Nottingham NG12 5GG, United Kingdom.

[6] British Geological Survey, Maclean Building, Wallingford, Oxon, OX10 8BB, UK

[7] Geological Survey of Slovenia (GeoZS), Dimičeva ulica 14, SI–1000 Ljubljana, Slovenija.

[8] Geological and Cartographic Institute of Catalonia (ICGC), Parc de Montjuïc, E-08038, Barcelona, Spain.

[9] Geological Survey of Belgium (RBINS-GSB), 13 Jennerstraat, 1000 Brussels, Belgium.

[10] Geological Survey of Sweden (SGU), Kiliansgatan 10, 223 50 Lund, Sweden.

[11] Czech Geological Survey (CGS), Klárov 3, 11821 Praha, Czech Republic.

[12] Geological Survey Ireland (GSI), Beggars Bush, Haddington Road, Dublin 4, Ireland.

[13] TNO, PO Box 80015, 3508TA Utrecht, The Netherlands.

[14] Geological Survey of Slovakia (SGIDS), Mlynská dolina 1, 817 04 Bratislava 11, Slovakia.

[15] Department of Environmental Sciences, Applied and Environmental Geology, University of Basel, Switzerland.

*****_Corresponding author_

a.garcia@igme.es

Phone: +34 976.55.51.53 Nº fax: +34 976.55.52.82

Abstract

Successful electrification of cities heating and cooling demands depends on the sustainable implementation of highly efficient ground source heat pumps (GSHP). During the last decade, the use of shallow geothermal energy (SGE) resources in urban areas has experienced an unprecedented boost which nowadays is still showing a steady 9% market growth trend. However, the intensive market incorporation experienced by this technology entails different responsibilities towards the long-term technical and environmental sustainability in order to maintain this positive trend. Here we present a SGE management framework structure and a governance model agreed among 13 European Geological Surveys, providing a roadmap for the different levels of management development, adaptable to any urban scale, and independent of the hydrogeological conditions and the grade of development of SGE technology implementation. The management approach reported is based on the adaptive management concept, thus offering a working flow for the non-linear relationship between planning, implementation and control that establishes a cyclical and iterative management process. The generalized structure of the SGE management framework provided allows the effective analysis of policy to identify and plan for management problems and to select the best management objectives, strategies and measures according to the policy principles proposed here.

Keywords: Shallow geothermal energy, thermal management policies, renewable energy resources, resource governance

1. Introduction

Evidences of anthropogenic climate change with detrimental consequences for human health and world's ecology requires urgent action on a global scale. Specifically, the reduction of CO_2 emissions is one of the main needs and worries (IPCC, 2013). Pursuing the decarbonisation of the energy sector is recognised as a decisive measure, which will need to transform the global energy sector from fossil-based to a zero-carbon system, also known as "sustainable energy transition" (IRENA, 2014). Electrification, when combined with electricity production coming from renewable sources, is an emerging key driver for the acceleration towards a sustainable energy transition. Geothermal heat pumps use the shallow subsurface as a heat source/sink for the air-conditioning of buildings and other human infrastructures. This technology an efficient thermal energy transference from the internal energy of rocks, soils and groundwater to the infrastructures, and vice versa. The amount of thermal energy contained within a depth up to a 400 m is known as shallow geothermal energy (SGE). There are two main categories or technologies exploiting SGE resources (Sanner et al., 2003). The first type, known as ground-coupled heat pumps (GCHPs) or , simply, closed loop systems, uses borehole heat exchangers (BHEs) to transfer thermal energy between the installation and the surrounding subsurface acting as a heat source/sink. The BHE typically consists of a 50-150 m vertical (or horizontal) borehole where u-pipes or coaxial pipes, connected to the heat pump and filled with a circulating heat carrier fluid, are introduced into the subsurface. The second type, known as groundwater heat pumps (GWHP) or open loop systems, extracts groundwater to take advantage of its great heat capacity, thus creating an efficient heat exchange with the installation. Once heat has been extracted or dissipated, water is usually reinjected back into the aquifer.

The number of SGE systems has been steadily rising for the past two decades (Bayer et al., 2012; Lund et al., 2011; Rybach, 2015; Sanner et al., 2013). Between 2010 and 2015, the total installed capacity of geothermal heat pumps on a global scale increased at an annual rate of 13.2%, reaching 50,258 MWt (Lund and Boyd, 2016), which represents 4.19 million equivalent installed 12 kW units (typical for residential/domestic use).

Inevitably, any heat transfer produced during the operation of a SGE will produce a temperature change in the subsurface media (Banks, 2012; Rivera et al., 2017; Stauffer et al., 2013). Most systems documented present subsurface and groundwater temperature changes in the range of 4 to 8 K above or below the undisturbed subsurface temperature. Nevertheless, greater changes of 13 and 25 K can also be found (García-Gil et al., 2016b; García-Gil et al., 2014). These thermal impacts do not only induce changes in temperature-dependent physical properties of groundwater (Carslaw and Jaeger, 1986; Hecht-Méndez et al., 2013), but also hinder the design, optimization, and performance of both GCHP (Li and Lai, 2015; Yang et al., 2010; Zhang et al., 2014) and GWHP (Lo Russo et al., 2014; Lo Russo et al., 2012; Piga et al., 2017; Pophillat et al., 2018) systems. Indeed, temperature anomalies in the subsurface produced by the systems can affect their own performance (Casasso and Sethi, 2015; Galgaro and Cultrera, 2013) or that of other nearby SGE systems. Such processes in general are referred to as “thermal interferences” and have been identified and modelled in different cities (Epting et al., 2013; García-Gil et al., 2014; Herbert et al., 2013; Mueller et al., 2018; Sciacovelli et al., 2014). The intensive use of the shallow subsurface in urban areas with high density of SGE installations can lead to thermal overexploitation of subsurface resources, thus endangering its regeneration. In this context, technical sustainability refers to reaching and maintaining the high performance of a geothermal system, i.e., to sustain production levels over long periods (> 30 years) (Rybach and Mongillo, 2006; Shortall et al., 2015) and maintain the thermal potential of SGE resources. In very low-enthalpy (shallow) reservoirs, stable production levels depend highly on the local hydrogeological conditions, which will influence the steady state regime during operations (Banks, 2009; García-Gil et al., 2015a; Hähnlein et al., 2010). Nevertheless, thermal interference between systems might also compromise technical sustainability of the systems, especially in urban environments where SGEs are affected by and contribute to subsurface urban heat island (SUHI) effects (Menberg et al., 2013; Zhu et al., 2011).

Thermal anomalies produced SGE systems will change kinetics and thermodynamic equilibria of existent geochemical reactions (Appelo and Postma, 2005; Langmuir, 1997). Endothermic and exothermic reactions controlling major elements, heavy metals and trace elements contents have all been related to geothermal exploitation in the field (García-Gil et al., 2016b; Saito et al., 2016) as well as in both column (Bonte et al., 2014) and batch laboratory experiments (Griebler et al., 2016). In addition, GWHPs where extracted groundwater is re-injected into the aquifer after heat transfer could also cause the exsolution of CO_2 or a gain in O_2 by inducing mineral precipitation (Abesser, 2010; García-Gil et al., 2016a) or preserving existing emerging organic contaminants (García-Gil et al., 2018a), if groundwater is not properly insolated from oxic atmospheric conditions, as well as many other temperature-driven geochemical reactions. During GWHPs systems operation mixing processes in groundwater can also be triggered (Bonte et al., 2011).

All subsurface ecosystems, together with groundwater-dependent ecosystems on the surface, can be affected by thermal impacts produced by SGE exploitation. It has been shown that elevated groundwater temperatures downgradient from GWHP systems impacted the composition of microbial communities in groundwater, as well as their diversity in an oligotrophic aquifer (Brielmann et al., 2009). Although subsurface temperature changes of up to ±6 K have been assumed to be acceptable by the latter authors, wider ranges have not been studied. Microbiological contamination studies assessing the effect of GWHPs on pathogen bacteria contents have shown a relative decrease of their concentration inside thermally affected areas (García-Gil et al., 2018b).

An overview of the legislation framework on SGE at the European level (Haehnlein et al., 2010; Tsagarakis et al., 2018) has shown an extremely heterogeneous legislation as well as discordant regulations, standards, and institutional support. Existing regulations show a high inconsistency in case of such aspects as: minimum distances between systems (5–300 m) and tolerable temperature changes in the subsurface (3-10 K). Furthermore, most countries in Europe have no legally binding regulations or even guidelines. The lack of an unified and scientifically-based policy among the European countries acts as a barrier for the development of the SGE market (Jaudin, 2013). This fact highlights the urgent need for the improvement of the legal framework for regulation of SGE installations and subsurface heat more widely.

Nevertheless, effort has been invested by the scientific community to develop sustainable management concepts addressing this problem. A first sustainable geothermal energy use strategy based on the precautionary principle, which implies an intrinsic principle of the European Water Framework Directive (EU-WFD, 2000), was proposed by Hähnlein et al. (2013). The strategy follows a systematic licensing procedure based on the type, usage and heating capacity of the exploitation system considered. Depending on these variables, the procedure would require more or less exhaustive technical and/or environmental assessment before licensing. To perform any technical or environmental assessment it is necessary to understand the thermal regime of the subsurface and to describe its ‘‘*present state*’’ with reference to a derived potential natural state (Epting and Huggenberger, 2013). The complexity of thermal regimes, especially in urban areas, has become a rising challenge since there are a high number of transient boundary conditions to account for, such as river-level variations (García-Gil et al., 2014), deep and hydro-insulated building foundations and infrastructure (Attard et al., 2016; Epting et al., 2017c), heat-transfer processes of the unsaturated zone (Rock and Kupfersberger, 2018), and the impact of SGE systems themselves (Lo Russo et al., 2014; Muela Maya et al., 2018). As an introduction of the equity policy principle, a relaxation factor was included and applied to a generalised licensing procedure using new thermal impact indicators (García-Gil et al., 2015b). The relaxation factor concept which was originally tested for the city of Zaragoza, Spain, (García-Gil et al., 2015b) was also successfully applied for the city of Basel, Switzerland (Epting et al., 2017a; Epting et al., 2018). In addition, a balanced sustainability index (BSI) was proposed as a management indicator applicable to GWHP systems where a quantitative value of sustainability is assigned to each system considered in order to evaluate the intrinsic potential to produce thermal interferences (García-Gil et al., 2019). A methodology to establish a market of SGE usage rights was applied to the city of Barcelona in Spain (Alcaraz et al., 2016). Other management concepts in SGE exploitation include the following: the subdivision of aquifers into smaller bodies considered as management units for thermal resources in order to effectively manage urban aquifers, the definition of the thermal propagation lag concept due to the differences of the timing of thermal signals with respect to groundwater flow; the thermal memory effect accounting for the time required to achieve a new thermal equilibrium in the aquifers managed, and the thermal fingerprints concept with regard to other temperature fluctuations in the subsurface due to boundary conditions in the managed groundwater body that are not genetically related to geothermal activity (Epting et al., 2017b).

The management of SGE resources is a collective action problem (and solution) requiring the involvement of governments, stakeholders, businesses and communities to integrate their activities to achieve the SGE sustainable development goals. In this context, the governance of SGE resources is crucial to establish the distribution of power and responsibilities between the science, policy, and civil society spheres in order to define the process of decision-making and implementation. To our knowledge, the current governance of SGE in Europe has not been addressed to a sufficient degree in the literature to date, and it is important to discuss the establishment of the governance principles and fundamental rules that will guide decisions to build consensus and market stability.

The main purpose of this paper is to analyse and identify the elements of proper governance for SGE resources management. To achieve this goal, first an exhaustive complete and novel management framework structure based on four policy principles was investigated and proposed. The management structure provided by this work prioritizes each policy into plausible management strategies, management objectives and management problems, followed by a list of management measures (or tools) that decision-makers can analyse during their management planning phase. All management concepts considered in this structure were included in a questionnaire designed to measure their degree of relevancy, based on the assessment of experts representing 13 European geological survey organizations. The results of the questionnaire were used to assign a relevancy score to each management concept listed. The final contribution of this research is a novel harmonized management structure and a governance model of SGE resources based on an adaptive management approach. This approach is constituted by the interaction of a management planning cycle combined with an implementation and control cycle, both specifically oriented to SGE resources and implemented taking into account its specific features as a renewable natural resource. This contribution aims to be useful for the management process that is introduced and discussed in this manuscript, according to the relative relevancy scored by the experts and obtained from the questionnaire´s survey. The key output from this work is a set of principles that will be used as a basis for adaptive SGE resources governance and will serve to establish a road map for the development of SGE management plans in urban environments.

2 Governance of shallow geothermal energy resources

2.1 Policy principles

To achieve a holistic management system for SGE resources, the first step is to define a number of key policy principles, and for that reason four main ways in which the use of SGE resources can preclude sustainable development presented below.

Firstly, the intensive and biased exploitation of SGE energy resources towards heating or cooling in urban areas can be interpreted as a reduction (or deficit) of renewable energy reserves. The scarcity associated could then compromise the access to this resource for a few decades. The first policy principle proposed is the "*Sustainable development and exploitation of SGE resources*". This policy attempts to prevent the following management problems; (I) geothermal overexploitation and unsustainable development, (II) negative thermal interferences and (III) inefficient use of geothermal resources.

Secondly, SGE use can result in threats to human health or in a reduction of the quality of the natural environment in general. The management problems arising around this issue include the (I) hydrodynamic mobilization of existing contamination of the aquifers due to pumping and injection of groundwater (changing groundwater dynamics), drilling and installation of wells. In contaminated areas, these wells can trigger the movement of contaminant plumes, due to groundwater flow. SGE use can also unleash homogeneous and heterogeneous geochemical reactions which eventually might increase the contents of existent (II) inorganic trace metals, (III) organic and (IV) microbiological contamination as additional management problems. (V) Thermal groundwater discharge to surface water bodies might lead to a management problem affecting groundwater-dependent ecosystems. Furthermore, SGE activity could make a (VI) contribution to SUHI effect. These six management problems would require a second policy response; consequently, the "*Environmentally friendly use of SGE resources*" is proposed to deal with these issues.

A third way to achieve sustainable development goals of SGE is to address potential conflict between new and other pre-existing or higher priority uses of the subsurface in urban areas. Management problems arising from this issue are as follows: SGE systems could compromise (I) groundwater quality as water supply or other (II) groundwater use conflicts such as irrigation, industrial, recreational uses, among others. Furthermore, SGE use can compromise (III) geochemical impacts associated with induced subsidence or generate different (IV) impacts on subsurface infrastructure. Potential conflicts with other urban subsurface uses should be coordinated and, therefore, the "*SGE coordination with other urban subsurface uses*" is introduced as a third key principle policy.

Finally, the sustainable development of SGE depends on the successful application of the management approaches planned. Therefore, the fourth policy proposed is to adopt a "*Successful SGE management approach*". The different management problems compromising the successful application of management plans considered in this work are: (I) managing in the context of data-poor urban subsurface bodies, (II) conflicts of interests, (III) inefficient management of SGE resources, (IV) applying appropriate management measures whilst keeping in balance with site-specific conditions, (V) disabling environment, (VI) uncertainty and (VII) illegal activity and heavy enforcement costs.

2.2 Structure of the SGE management framework

The general structure of the proposed management framework stems from the conceptual development of each of the management policies described above using a hierarchical system (Fig. 1). The highest rank level is assigned to management policies. A management problem can be assigned to each policy as a second rank level. Since management problems are identified within the system, decision-makers are expected to establish their own policies. Once a policy has been defined, decision-makers could propose management objectives following the policy's direction. Considering that one or more objectives can be assigned to rectify a management problem, here we propose the management objective as a third level. To achieve each management objective, decision-makers can enact different strategies (fourth level) for which specific management measures (fifth level) can be proposed. As an example, following the branch developed in Figure 1, the strategic allocation of SGE systems, licensing procedures and planning of district heating grids are three possible measures to follow the strategy of sustainable development. This strategy can be adopted to fulfil the objective of preventing overexploitation. This objective will contribute to the management problem of geothermal overexploitation and unsustainable development if detected in a managed system. Then, all those management measures would be justified by the *"sustainable development and exploitation"* policy. This structure provides clarity in the decision, thus making this process transparent to stakeholders (including the systems users).

An exhaustive conceptual review of all management concepts has given rise to a complete list of 289 management elements or concepts organized in 5 hierarchical management levels: 4 SGE management policies; 21 management problems; 27 management objectives; 58 management strategies; and 179 management measures considered of importance.

Management policies and problems are provided above and a complete list of objectives, strategies and measures that complete the structure of the management framework proposed here are provided as supplementary material (Table S1).

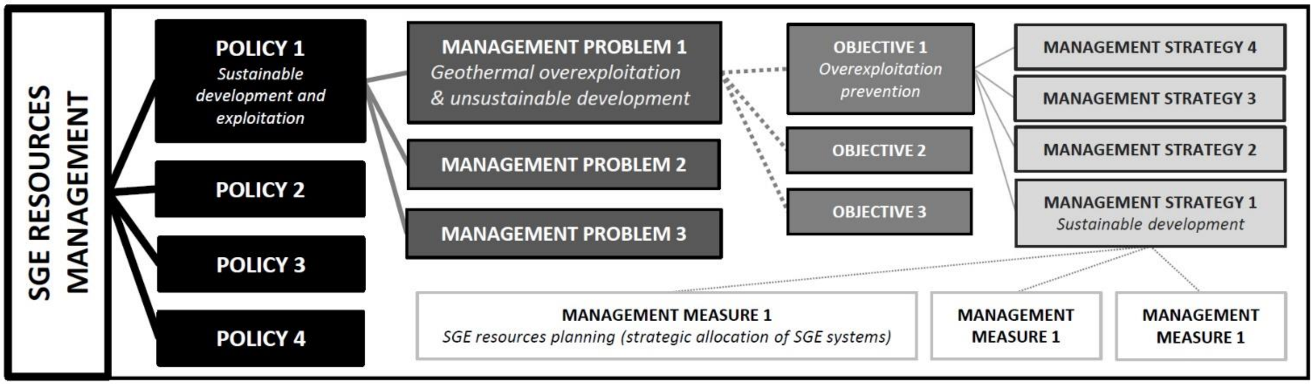

Fig. 1. Simplified structure of the management framework proposed for shallow geothermal (SGE) resources, showing 5 management levels. Only the management measures proposed following one of the four management strategies are represented in this example. This simplification is applied to the rest of the management levels. Only extended management levels developed in the diagram are named. The complete structure of the management framework arranged in tables for each management policy is provided in the supplementary material (Table S1).

2.3 Governance model of SGE resources

The adaptive management approach (Holling and Programme, 1978; Walters, 2001) is the most accepted and applicable path to govern natural and renewable resources in highly dynamic and complex environments. This approach offers a working framework for non-linear relationships between planning, implementing and controlling, thus establishing a cyclic and iterative activity during the management process. Therefore, in order to define the decision-making and the decision-implementation processes of SGE resource management, it is proposed to follow the adaptive management cycle introduced for renewable resources, e.g., Savenije and Van der Zaag (2008) for water resource management (Fig. 2).

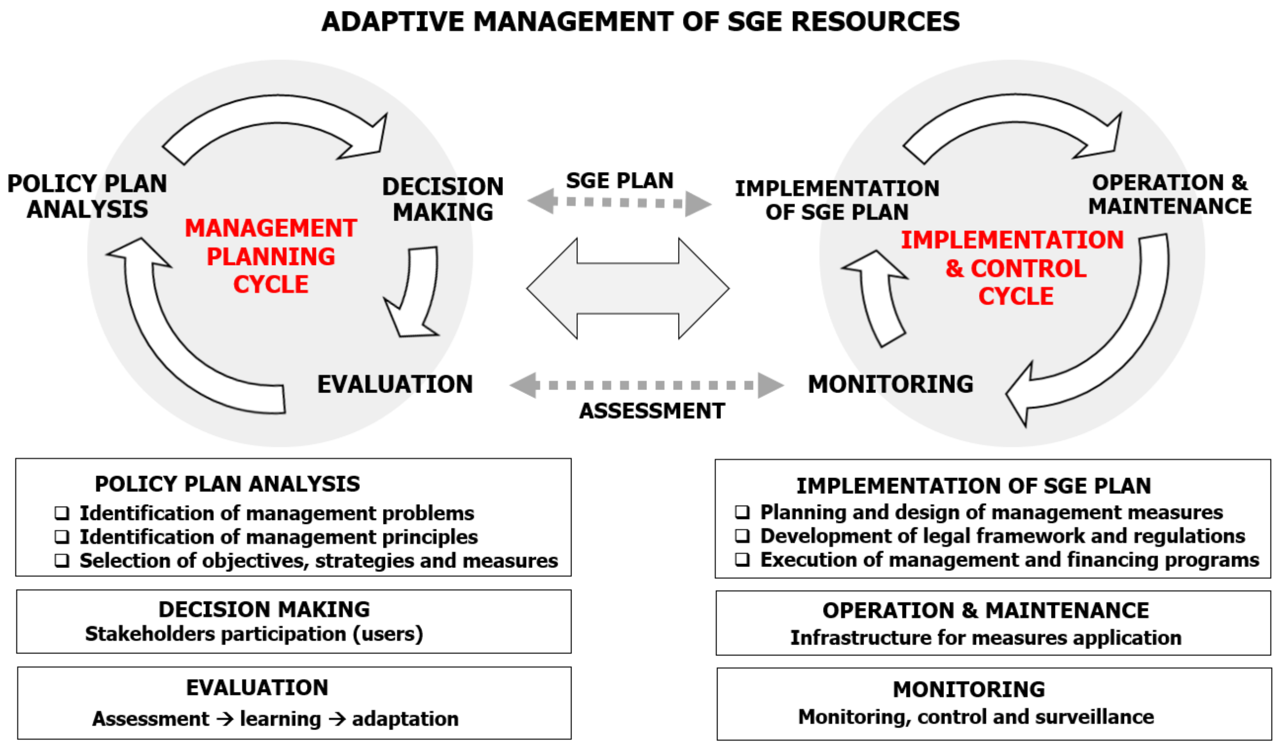

Fig. 2. Conceptual diagram of the proposed double-adaptive management cycle concept for SGE resources based on Savenije and Van der Zaag (2008) .

In the case of SGE resource management, two main activities or processes are proposed: the process of management planning and the process of implementation and control.

Management planning consists of three cyclic and iterative tasks (Fig. 2). The first task is to perform a policy plan analysis identifying appropriate management problems and selecting the proper management objectives, strategies and measures according to established policy principles. This task is crucial and thus it also has to provide a generalized structure for the SGE management framework as a checklist or roadmap to set the foundations for the SGE management plan (Table S1). Decision-makers can select the management concepts from this general management framework structure affecting their specific conditions. Furthermore, decision-makers can also find it useful as a checklist to assess all possible issues related to SGE exploitation that might not have been considered in a first approach. During the planned policy analysis, it is also necessary to obtain a holistic view of SGE exploitation in the local context. This gathers knowledge on the existing SGE systems, estimates the SGE potential (resource assessment) and obtains a view of the existing socioeconomic framework. Once an initial assessment has revealed the existing problems, SGE resources exploitation trends and management policies to follow need to be analysed. The second task is to go through a decision-making process to prepare and adopt a strategic action plan by considering the management measures to be adopted. The third task in the management planning cycle is the evaluation of the effectiveness of the management plan adopted, i.e., to evaluate the effectiveness of the management measures according to the management objectives. This evaluation is the keystone to adaptive management that ends the planning cycle and so decision-makers learn about the potential deficiencies of the managed system that will be considered in the next planning cycle.

After the planning cycle is completed, an implementation and control cycle start (Fig. 2). The main task in this cycle is the implementation of the management action plan by establishing a detailed design and implementation of the planned management measures, to promote enforcement of laws and regulations and to strengthen the enabling environment and governance. The second task is to maintain operative the possible infrastructure required to implement the planned management measures. The task that closes this cycle is monitoring. By monitoring, controlling and surveying, the resources demand and trends can be quantified and the effectiveness of the implemented management plan assessed. Furthermore, monitoring outputs are crucial for the evaluation and policy plan analysis tasks from the planning cycle.

The reason why those cycles are separated is to facilitate the whole management process. After the first planning cycle finishes, each cycle can evolve independently as information keeps flowing between cycles. For example, two implementation and control cycles can be going through the same strategic action plan defined in the first planning cycle, or two planning cycles could be required to initiate a realistic implementation and control cycle.

3 Data and methods

A compendium of renewable resource management concepts related to SGE integration was generated by searching scientific articles following Somogyi et al. (2017) procedure. Scientific articles were searched in the database of sciencedirect.com, Scopus and Web of Science databases on 6th December 2018. The search criteria used was limited to the terms “heat pump” and “geothermal” or “ground source”. A total the number 2068 publications were found.

An exhaustive questionnaire on management policies (block I) and management cycle (block II) related to SGE resources was issued to 13 European geological surveys to develop and harmonize a generalized governance policy approach on SGE resources. The surveyed institutions included the Geological Survey of Spain (IGME), Austria (GBA), Croatia (HGI-CGS), Catalonia (ICGC), United Kingdom (BGS-UKRI), Belgium (RBINS-GSB), Slovenia (GeoZS), Sweden (SGU), Poland (PIG-PIB), Czech Republic (CGS), Ireland (GSI), The Nederlands (TNO) and Slovak Republic (SGIDS). The first block of the questionnaire, oriented towards management policies, was structured into the following four policies: (I) sustainable development and exploitation; (II) environmentally-friendly use of SGE resources; (III) coordination of SGE exploitation with other urban subsurface uses; and (IV) successful management approach. This block of the questionnaire considered a total of 289 management concepts organized in 4 hierarchical levels of detail which were, from top to bottom: four exposed SGE management policies; 21 management problems; 27 management objectives; 58 management strategies; and 179 management measures considered of importance. The second block of the questionnaire, oriented towards the management process, considered a total of 151 management concepts related to the adaptive management of SGE resources. Each Geological Survey was asked to evaluate each management concept using a 9-rank scale of relevance (1 = not relevant and 9 = very relevant). The survey was undertaken between December 2018 and January 2019.

The results from the 13 questionnaires, containing the 9-rank scale of relevance score for each management concept, were transformed to a proportional percentage scale where a rank value of 1 accounted for 0% relevance, a rank value of 9 accounts for 100% relevance, and so on. This allowed assessing the results obtained from the questionnaires and describing them in terms of descriptive statistics, by calculating the arithmetic mean value and standard deviation of the data. Based on the average values assigned to each management concept, the questionnaire was reordered by sorting the management concepts of each level, starting with the most relevant concepts. This reorganization maintaining the four hierarchical levels of detail in the first block allowed to obtain a management concept checklist for SGE managers.

The principal component analysis (PCA) method was applied to analyse the national geological surveys' appraisal to the management problems proposed in this work (IEA, 2018). This method allowed investigation of the variance found in the data obtained from the project survey and was conducted by using a smaller number of uncorrelated variables (PC). The principal components obtained during the application of the method helped in the interpretation and analysis of the observed appraisal of problems found in the management of SGE resources. The varimax rotation method was used to maximize the squared factor loadings for each factor (gamma = 1). Statistical significance was established for *p*-values below 0.05. All the statistical analyses were performed using SPSS Statistics version 20.0 software (IBM; Armonk, New York, USA).

4 Results and discussion

4.1 Structure of the SGE management framework

Results obtained from the survey on the relevance assessment of the different management concepts considered in the structure framework are shown for each management policy presented in this manuscript in Table I, Table II, Table III and Table IV, respectively. The complete list of management measures associated to each strategy is provided as supplementary material (Table S1). In this manuscript, only relevant (>70% on the relevance assessment) management concepts are discussed.

The results obtained from the survey (Table I) indicate that the most important problem endangering the sustainable development and exploitation of SGE resources is geothermal overexploitation and unsustainable shallow geothermal development. This problem can be overcome preferably by establishing two management objectives. Firstly, the highest rated management objective (85%) is to prevent overexploitation of SGE resources by considering the sustainable shallow geothermal development as the most relevant strategy to be adopted. The best way to follow this strategy is to control the allocation of SGE exploitation systems according to an established plan. Another measure would be to limit the access to the resource by licensing procedures. In this sense, input controls should be considered, including the size and number of SGE systems and the exploitation technology used. These results suggest the use of a rights-based approach to manage SGE resources by allocating limited rights in a particular city area or geological volume. The shift from open access of new SGE users towards a managed access regime would limit the number of participants with rights and responsibilities to exploit SGE resources and, thus, it would prevent overexploitation. A second management strategy found relevant is the identification of areas at risk of overexploitation and, as a preventive measure, the mapping of intensively exploited areas is proposed.

Table I. Results obtained from the survey on the relevance scores for the different management levels: management problems (PROB), management objectives (MO) and management strategies (STGY), as assessed by 13 national geological surveys for the sustainable development and exploitation policy.

The second management objective in order of relevance (78%) is the long-term sustainable use of SGE resources. To achieve this objective, the highest rated strategy is understanding the heat and hydraulic regimes in the subsurface volume being managed, thus requiring research and extension services. The second strategy, in order of perceived importance is the prioritization of SGE demands during the licensing of the SGE systems. The strategy of sustainable development and the measures considered for the overexploitation prevention objective are also considered to be important to this objective. The last most relevant strategy would be to enforce a rights-based system where licensing procedures are considered. It is observed that the adoption of a licencing procedure measure contributes to the improvement of both management objectives gaining greater interest for the efficient management of SGE resources. Additional relevant measures are the assignation of exploitation rights during the licensing process and a limitation on the total allowable unbalanced heat transfer to the subsurface during a year of operation. The balanced heat transfer of heating and cooling have been identified as good indicators of sustainability for SGE systems (García-Gil et al., 2019). The second most important problem to reach a sustainable development and exploitation of SGE resources are thermal interferences. The most decisive management objective to be considered is the reduction of thermal interferences by adopting precautionary measures, i.e., limiting the number of SGE users. On one hand, several precautionary measures are already considered in international regulations (Haehnlein et al., 2010), such as determining the minimum distance between borehole heating exchangers, operation wells, or limitations on temperature changes in the subsurface and temperature differences between extracted/reinjected water. A significant precautionary measure proposed is to monitor groundwater temperatures between two adjacent GWHP systems. On the other hand, increasing the existing distance restrictions for thermal interferences is again considered as the most crucial measure, followed by the adoption of threshold values such as maximum/minimum operation temperatures in SGE systems, and the establishment of an integrated monitoring, surveillance and control system for subsurface temperatures. A second management objective recommended is around the minimization of thermal short-circuiting (auto-interference and/or thermal recycling) by designing an adequate SGE systems set-up and a licensing process that considers a thermal short-circuit assessment (especially relevant to fracture flow-dominated aquifers). Other management objectives of importance when trying to reduce thermal interferences include minimizing them by the reduction of unbalanced energy transfer of neighbouring installations and efficiently using SGE resources.

The third management problem in order of perceived relevance is the inefficient use of geothermal resources, while the proposed management objective is the adequate use of SGE resources. To achieve this objective, it is recommended to follow a management strategy based on the principle of efficiency. Thermal short-circuit assessment during the licensing process and increasing COPs of SGES as much as possible (through good design and thermal insulation of buildings) are the measures considered as being critical for this strategy.

The survey outcome (Table II) indicates that maintaining an environmentally-friendly use of SGE resources requires coping with arising threats to human health or the environment affected to SGE exploitation. There is a general agreement that hydrodynamic remobilization of existing contamination in aquifers due to the wells of GWHP systems is considered to be the most worrying management problem (88%). Open loop systems operating in contaminated sites might cause the spreading of existing contamination to other places, thus contributing to a potential groundwater quality decline in extended areas of the urban subsurface. Persistent pollutants such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) commonly occur in subsurface urban environments as point-source contamination (Bonneau et al., 2017; Schirmer et al., 2013), thus posing a real threat to groundwater resources as a water supply. In addition, hydrodynamic remobilization could also contribute to the release of mobilized groundwater contaminants into surface water bodies which are hydraulically connected (Engelhardt et al., 2011). The management objective linked to this problem is to operate SGE systems using good groundwater quality. The strategy to follow is to operate GWHP systems outside of contaminated areas by licensing and area closures measures. Evidence from field studies also showed the importance of ensuring a tight hydraulic circuit from abstraction to reinjection to avoid geochemical alterations and well clogging triggered by oxygenation (Casasso and Sethi, 2019).. In addition, adopting precautionary measures, such as monitoring of pumped groundwater quality by periodic sampling is recommended.

Table II. Results obtained from the survey on the relevancy scores for the different management levels: management problems (PROB), management objectives (MO) and management strategies (STGY), as assessed by 13 European national geological Surveys for the environmentally-friendly use of SGE resources policy.

The second most relevant problem this policy faces are the activities raising threats to human health or the environment in general (78%), while specific approaches to specific types of contaminants are not considered of special relevance. The objectives considered important to the general approach include the reduction of environmental impacts, followed by establishment of a cause and effect relationship for environmental impacts and the identification of potential subsurface quality deterioration. To reduce environmental impacts, two strategies are considered essential. The first one considers the use of precautionary measures, such as leakage tests of the closed-loop refrigerant tubing, specific regulations on the heat carrier fluid type, evaluation and risk assessment during the licensing process, operation depth restrictions, borehole sealing in decommissioning SGE systems, and establishment of specific regulations on borehole heat exchanger grouting and licensing. The second strategy consists in understanding how SGE exploitation impacts the ecosystem functions through research and extension services. Extension services are a key point, as they transfer research outcomes to stakeholders to prevent environmental problems, by means of providing advice and information programmes. Establishing the objective of finding a cause and effect relationship for environmental impacts is also seen as very relevant. This objective aims to reduce the uncertainty that can limit the benefits of SGE exploitation according to a precautionary principle embedded in the European union (TFEU, 2010). Therefore, the strategies suggested are to use the best available science for decision-making, and to study the physical, biological and chemical processes triggered by SGE use, both through monitoring and risk assessment and by using research and extension services. The third management objective considered relevant is the identification of potential subsurface quality deterioration, proposing the establishment of an environmental monitoring, surveillance and control system as a management strategy against this potential issue. The cost to set up, and the ongoing provision, of such services needs to be factored into the licensing, and must be in balance with the objectives and socioeconomic constraints of the region, embracing new advances in technology and data management, where possible, to make efficiency gains.

The results obtained from the survey (Table III) also indicate that the most critical problem, showing the highest score of 92% when facing the appropriate SGE coordination with other urban subsurface uses, is to maintain groundwater quality at acceptable levels for water supply. The management objective here is to maintain the groundwater quality standards for human consumption and the strategy proposed is to follow the precautionary approach. This would suggest banning any kind of SGE activity in protected areas for drinking water supply. The second management problem in order of scored importance (84%) is the consideration of plausible groundwater use conflicts related to irrigation, industrial, recreational or any other uses. General problems related to urban subsurface use conflicts also received a score of 74%. The management objective considered as most essential for this point was the prevention and control of crosscutting conflicts by making use of prevention and mitigation strategies. Hence, the management measures proposed are the mapping of urban subsurface uses and the assessment of the resulting mapped zones in the licensing process.

Table III. Results obtained from the survey on the relevancy scores for the different management levels: management problems (PROB), management objectives (MO) and management strategies (STGY), as assessed by 13 European national geological Surveys for the SGE coordination with other urban subsurface uses policy.

Survey results (Table IV) have shown that the most vital problem (with a score of 83%) to improve the successful management of SGE resources involves the management in the context of data-poor urban subsurface. Since subsurface datasets are currently very limited and expensive to obtain, and management of SGE resources is an emerging branch in science, it is necessary to provide an efficient management approach while efforts are made to improve data-poor contexts. To achieve this objective, improvement of reporting, assessment, collection and management of data protocols has been recommended. Other strategies considered relevant are the use of simplified management approaches such as implementation of simple statistics for the management of SGE resources as well as relying on the user's knowledge of the SGE system. Other strategies considered relevant are the use of simplified management approaches, the implementation of simple statistics to manage SGE resources and also relying on the knowledge of SGE system users. User knowledge such as installed capacity, mean flow rates or working temperatures of the systems could be of great interest in the first stages of SGE resource management. A second important (82%) management problem would be the conflict of interest between stakeholders, i.e., all the involved parties in the management process. To ensure the objective of reducing the number of conflict cases, considering the co-management of SGE resources has been proposed as a potential solution. This would make the resources become self-regulated thus diminishing the enforcement and increasing the compliance. Furthermore, co-management can be implemented by including the affected parties in the decision-making during all the planning process.

The third management problem in order of perceived relevance (76%) is the inefficient management of SGE resources. Management objectives suggested for this matter are to diminish enforcement problems and compliance by providing legal and economic certainty in the licensing process, and to achieve a flexible iterative management approach. The problem of dealing with management measures dependent to site-specific conditions has also been highlighted (75%). To mitigate this problem, establishing the objective of adapting the management measures to the specific local boundary conditions has been suggested. Finally, the last relevant (72%) problem potentially hindering the successful management of SGE resources is the disabling environment. To overcome a disabling environment, capacity building through development of appropriate policy and legal frameworks is considered necessary.

Table IV. Results obtained from the survey on the relevancy scores for the different management levels: management problems (PROB), management objectives (MO) and management strategies (STGY), as assessed by 13 European national geological surveys for the successful management approach policy.

Inevitably, each social community will attribute distinct relevance to the different management problems raised due to their own site-specific conditions and/or social priorities and concerns. To understand the different positions of the different national surveys on their approach for the management of SGE resources, a PCA was performed (Table V). Six significant main components, accounting for 91.0% of the total variance, were extracted according to the sharp bend found in the scree plot for six of the components. The first two PC explain 56.4% of the variation observed in the data, and the contribution of each geological survey is represented in a score plot in Fig. 3. The first component, accounting for 40.5% of the total variance, is marked by a relatively high tendency of the geological surveys when rating the relevance of the management problems related to a successful management approach and an environmentally-friendly use of SGE resources policies. In particular, the dependence of the management measures to site-specific conditions, uncertainty, managing in the context of data poor urban subsurface body and enhancement of existent microbiological contamination. The second component is marked by low loadings of successful management approaches and high loadings of environmentally friendly use of SGE resources and SGE coordination with other urban subsurface use policies. In particular to inefficient management of the SGE resources, conflict of interest for the first policy and activities raising threats to human health or the environment and geotechnical impacts for the rest of policies. The Score-loading plot (Fig. 3) shows how geological surveys are split in two clusters. The first one includes PIG-PIB, ICGC, GBA, GSI, GeoZS, HGI.CGS, BGS-UKRI and IGME (known as group A), showing a relatively positive trend towards a positive rating for the management problems of the first component. The second group would consist of SGIDS, CGS and HGI-CGS (known as group B), presenting a flat tendency in the first component and a negative relative tendency for the second component. In contrast, SGU shows a clear negative tendency relative to other surveys for both components. RBINS-GSB shows a negative tendency for the first component but a very high tendency for the second component.

Table V. Component loading for management problems that determine the management approach adopted by the different European national geological Surveys when considering four main management policies. Results obtained from principal component analysis (PCA) explaining % of the variance found in 12 valid cases.

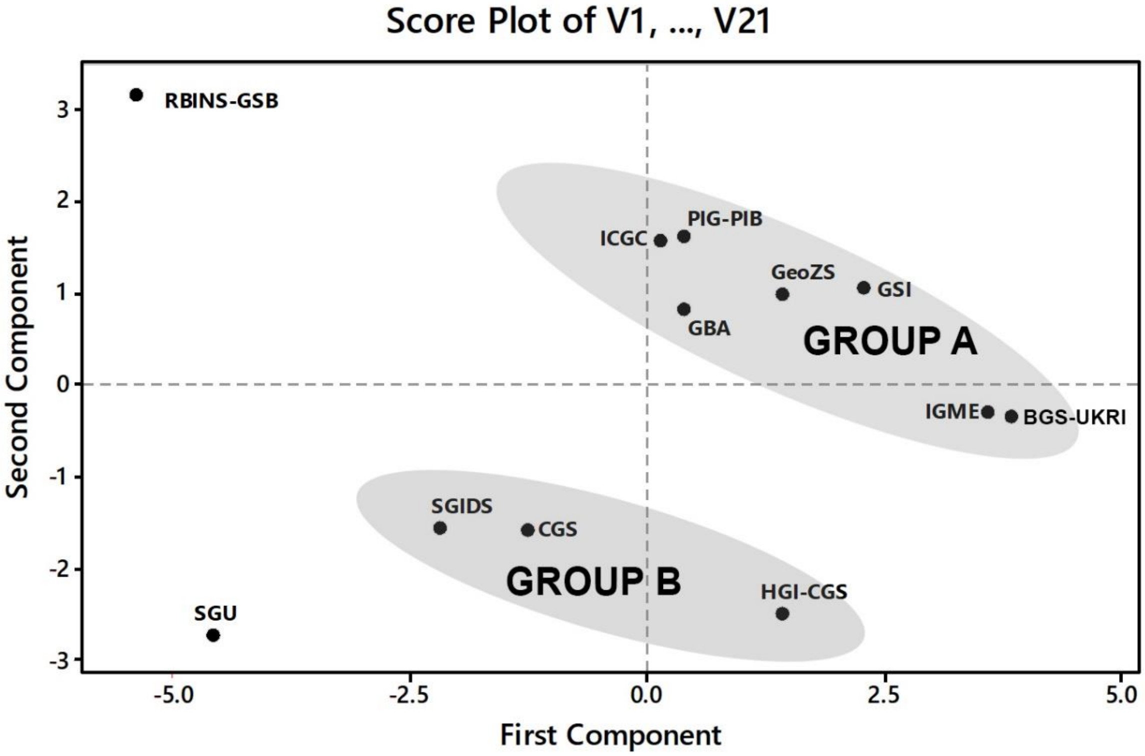

Figure 3. Principal component analysis (PCA) score plot. The plot shows the tendency of each Geological survey in their rating of management problems separated into two clusters, group A and B. Geological Surveys abbreviations stand for Spain (IGME), Austria (GBA), Croatia (HGI-CGS), Catalonia (ICGC), United Kingdom (UKRI), Belgium (RBINS-GSB), Slovenia (GeoZS), Sweden (SGU), Poland (PIG-PIB), Czech Republic (CGS), Ireland (GSI) and Slovak Republic (SGIDS).

4.2 Governance of SGE resources

There is a general consensus in the relevancy (82%) when referring to the adaptive management approach for the governance of SGE resources, where the learning process consist in monitoring and evaluating to make iterative adjustments within the planning process.

The first phase of the planning cycle (Fig. 2) is based on analysing the policy plan to follow. This analysis starts with the problem of identification and assessment. For that purpose, it is recommended to go through the management problems checklist (e.g., Table S1 provided as supplementary material). To effectively identify and assess these management problems of the system managed, performing a SGE resource assessment to provide past and current status of SGE resources considering overexploited extent and its plausible potential future trends is considered essential (84%). In addition, having proper knowledge on the local context of SGE systems, including the current status and trends of the SGE resources exploited is also considered relevant (84%). This also includes identifying the conflict areas between SGE systems and the hydrogeological characterization of the shallow urban subsurface. This approach requires strong public environmental regulation and geoscience institutions, and continuity and science capacity in municipal and national environmental agencies. Afterwards, in the establishment of management objectives, it is considered important to clearly define the objectives, which should be specific, measurable, achievable, realistic and time-related. Moreover, management objectives should be directly linked to management measures, listing the expected outcomes. The final task for the analysis of the policy plan, i.e. the identification of possible strategies and measures, appears as essential to identify the priorities upon which to focus effort and resources. The second phase in the planning cycle is the decision making. In this phase, the participation of stakeholders during all phases should be considered important (78%).

In the implementation and control cycle (Fig. 2), the first phase consists of the implementation of policies and it is considered most relevant by the surveyed group (82%) to perform such implementation in the context of data-poor environments. It is needed that managers improve the overall SGE data system by using data collection and reporting these data in accessible and transferable formats on easy-to-access open platforms. It is also recommended to use simple management approaches based in simple statistics to manage the SGE resources and to rely on the knowledge of SGE systems users. In the last phase of this cycle, the results of the survey see the relevance (78%) of setting a monitoring, control and surveillance system under a low financial requirements framework relying on cost effectiveness, payer and low-cost approaches. The monitoring, control and surveillance system will provide compliance through instrumental measures. Finally, the monitoring of effectiveness of the management measures planned is described as a very important aspect (76%). Complete results obtained from the survey are provided as supplementary material (Table S2).

4.3 Range of application of the results obtained

The degree of relevancy scored by the experts from the 13 European geological survey organizations surveyed may be considered as a guideline for decision-makers when these are contemplating the implementation of the management concepts compiled in this work. Each case study will present its singularities and therefore its own priorities for the managers, which will probably be different to the general trend observed in this work. The management structure provided aims to help seeing the big picture of the SGE resources governance, especially by introducing the concept of adaptive management, which is characteristic of the sustainable management of natural resources. An iterative management approach requires the definition of the general framework, where resource managers are expected to make decisions and this work provides it in a generalized and flexible way, including the additional guidelines from an expert panel. The experts’ scores could be considered as a starting point for decision makers in the first stages of the planning cycle. As specific knowledge is gathered for each specific case managed, new relevancy scores specific to that case could be considered.

5. Conclusion and Policy Implications

In this work, the complexity of the thermal regime in the shallow subsurface of cities and the importance of its implications in understanding renewable energy resources, together with the existing environmental barriers to SGE development, have been introduced and discussed. The steady growth and implementation of SGE systems in urban environment has triggered major concerns about the long-term technical, environmental, and even economic and social sustainability of this technology. The existing legal frameworks all over the world have failed to some degree to provide a scientific-based solution to this problem and aimed to use simple approaches, often with their roots in groundwater resource management, that have ended in disperse incoherent legal enforcements. Although the management concepts developed in those legal frameworks are appropriate, the fixed thresholds proposed are still not scientifically-based and are sometimes questionable, thus failing to reduce or manage uncertainty among users, managers and the industry. In this work, a complete adaptive management approach for the governance of SGE resources, harmonized by 13 European geological surveys has been presented. First, a complete management framework structure configuring a roadmap for policy makers is proposed. The management structure mainly consists of an open but exhaustive checklist of management problems, objectives, strategies and measures organised according to four policy principles proposed here; (I) *"Sustainable development and exploitation of SGE resources",* (II) "*Environmentally friendly use of SGE resources"* (III), "*SGE coordination with other urban subsurface uses"* and (IV) "*Successful SGE management approach"*. This management framework structure is then proposed in the management process by the definition of a governance model adaptable to data-poor systems and the uncertainty associated. This governance model follows a double-adaptive management cycle to define the process of decision-making in the planning stages and the decision-implementation processes.

The discussion made on the governance of SGE resources shows the potential need to enforce the elaboration of SGE management plans by legal frameworks and regulations, thus appearing as more crucial than the definition of fixed threshold values for all plausible scenarios. To this end, enforcements should preferably be imposed throughout an adaptive management approach where transparency, co-management and research as well as extension services guide the process.

The experience gained in the field of SGE exploitation has proven that the transition from fossil fuels to electrification of heating and cooling services in the cities cannot yet be achieved through technology advancement alone, as scientifically-based robust policies are needed to effectively implement SGE exploitation within city energy and climate plans. For that matter, the governance approach proposed shows a strong potential to support EU initiatives to contribute to the decarbonisation of the European economy.

6. Acknowledgments

Survey and data analysis were undertaken within the EU H2020 GeoERA project MUSE – Managing Urban Shallow geothermal Energy. MUSE has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 731166 under the terms of GeoERA programme – ERA-NET Cofund Action. This research was also partially supported by the research group Geología Aplicada E01_17R recognized in the Spanish Autonomous Community of Aragon.

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Supplementary Material

Governance of shallow geothermal energy resources

*Alejandro García-Gil, Gregor Goetzl, Maciej R. Kłonowski, Staša Borovic, David P. Boon, Corinna Abesser, Mitja Janza, Ignasi Herms, Estelle Petitclerc,
Mikael Erlström, Jan Holecek, Taly Hunter, Vincent P. Vandeweijer, Radovan Cernak, Miguel Mejías Moreno and Jannis Epting*

May 29, 2019

Table S1. Complete list of management problems (PROB), management objectives (MO), management strategies (STGY) and management measures (MS) that completes the structure of the management framework.

MANAGEMENT POLICY: SUSTAINABLE DEVELOPMENT AND EXPLOITATION

LEVEL	NAME	RELEVANCE [-]
PROB	**Geothermal overexploitation & unsustainable development**	**85%**
MO	**-Overexploitation prevention**	**84%**
STGY	**▪ Sustainable development**	**83%**
MS	SGE resources planning (strategic allocation of SGE systems)	83%
MS	Licensing procedures (sustainable exploitation assessment)	81%
MS	Planning of district heating grids	57%
STGY	**▪ Identification of areas at risk of overexploitation**	**72%**
MS	Mapping of intensively exploited areas at risk of overexploitation	73%
MS	MSC system for subsurface/production temperatures (positive trends)	66%
MS	MSC system for exploitation regimes of SGE systems (positive trends)	64%
MS	MSC system for COP of SGE systems (positive trends)	62%
STGY	**▪ Control of exploitation efforts**	**65%**
MS	Limitation of new entry of SGE systems into potential conflict areas	70%
MS	Licensing procedures (exploitation limits enforcement)	70%
MS	MSC system for subsurface/production temperatures	67%
MS	MSC system for exploitation regimes of SGE systems	64%
MS	MSC system for COP of SGE systems (positive trends)	60%
STGY	**▪ Management of growing demand for SGE to pursue sustainability**	**65%**
MS	Limitation of heating/cooling capacity (Flow rates, T, ΔT)	77%
MS	Identification of the key drivers of the demand's change	61%
MS	Identification of the demand's current status and trends	60%
MS	Incentives to non-exploited areas	47%
MO	**-Long-term sustainable use of SGE resources**	**78%**

STGY	**▪ Understanding of heat and hydraulic regimes in the subsurface**		**84%**	
MS	Research and extension services	86%		
STGY	**▪ Prioritization of SGE demands**		**81%**	
MS	**Licensing**	**79%**		
STGY	**▪ Sustainable development**		**74%**	
MS	Licensing procedures (sustainable exploitation assessment)	73%		
MS	SGE resources planning (strategic allocation of SGE systems)	70%		
MS	Planning of district heating grids	58%		
STGY	**▪ Enforcement/compliance for a rights-based system**		**72%**	
MS	Licensing	81%		
MS	Exploitation rights	73%		
MS	Limit on total allowable unbalanced heat transfer per year	70%		
MS	Access rights	66%		
MS	Territorial resource rights	64%		
STGY	**▪ Control of exploitation efforts**		**65%**	
MS	Limitation of new entry SGE systems into potential conflict areas	76%		
MS	MSC system for exploitation regimes of SGE systems	72%		
MS	Licensing procedures (exploitation limits enforcement)	72%		
MS	MSC system for subsurface/production temperatures	71%		
MS	MSC system for COP of SGE systems (positive trends)	48%		
STGY	**▪ Long-term stability of production temperatures in SGE systems**		**63%**	
MS	MSC system for subsurface/production temperatures (no trends)	72%		
MS	MSC system for exploitation regimes of SGE systems (no trends)	68%		
MS	MSC system for COP of SGE systems (no trends)	57%		
STGY	**▪ Promotion of a balanced use of the resources**		**60%**	
MS	Encouragement of nested SGE systems (SGE systems inside heat plumes)	60%		
MS	Subsides to SGE systems reducing asymmetry of exploitation regime	57%		
MS	Fines and penalties to SGE systems with extremely biased exploitation regimes	27%		
STGY	**▪ Stand-still principle:**		**42%**	
MS	Management actions that will maintain or reduce SGE systems' COP	48%		
MS	MSC system for COP of SGE systems (minimum values)	43%		
MS	Management actions that require thermal (COP) impact assessment	41%		
MO	**-Recovery of sustainability in areas under overexploitation**			**64%**
STGY	**▪ Characterization of overexploited areas**		**63%**	
MS	Mapping of areas under SGE overexploitation	66%		
MS	MSC system for subsurface/production temperatures (unacceptable values)	63%		
MS	MSC system for exploitation regimes of SGE systems (unacceptable values)	63%		

MS	Identification of abandonment of installations (worst case scenario)	58%	
MS	MSC system for COP of SGE systems (unacceptable values)	46%	
STGY	**▪ Increase of SGE supply in areas under overexploitation (remediation)**		**48%**
MS	Subsides to SGE systems biased balance towards recovery	45%	
STGY	**▪ Reduction of overexploitation (mitigation)**		**45%**
MS	Nested SGE systems (Strategic SGE systems requiring heat inside heat plumes)	51%	
MS	Revokement/limitation of existing licenses	45%	
MS	Incentives for conflictive users to reduce unbalanced exploitation	44%	

PROB	**Thermal interferences**				**78%**
MO	**-Reduction of thermal interferences**			**77%**	
STGY	**▪Precautionary measures**		**88%**		
MS	Minimum distance between pumping and reinjected wells	88%			
MS	Limitation of the absolute allowed temperature range of the RJ water	88%			
MS	Minimum distance between the borehole heat exchangers	88%			
MS	Limitation of the allowed temperature change in the aquifer	82%			
MS	Limitation of the T difference between extracted/reinjected water	77%			
MS	Monitoring of groundwater temperature between two neighbor SGE systems	74%			
MS	Limitation on reinjection of used groundwater	66%			
STGY	**▪ Limitaion of the number of participants with rights and responsibilities**		**75%**		
MS	**Controlled access to the managed area**	**69%**			
STGY	**▪ Reduction of thermal interferences between/within exploitation**		**73%**		
MS	Distance restrictions between SGE systems	81%			
MS	Maximum/minimum operation temperature restrictions in SGE systems	78%			
MS	MSC system for subsurface temperatures (groundwater)	77%			
MS	Temperature change restrictions in exploitation regimes of SGE systems	73%			
MS	MSC system for subsurface/production temperatures	71%			
MS	MSC system for exploitation regimes of SGE systems (unacceptable values)	70%			
MS	Operation depth restrictions for SGE systems	60%			
MS	MSC system for COP of SGE systems	57%			
MS	Time-area closures (Protection areas for existent SGE installations)	50%			
STGY	**Allocation of limited rights to net annual heat transfer into the aquifer**		**56%**		
MS	Total Allowable Unbalanced Heat Transferred (TAUHT) per year	57%			
MS	▪ Soft TAUHT (guiding)	68%			
MS	▪ Hard TAUHT (obligatory)	49%			
MS	Input-output energy transfer controls	55%			
STGY	**▪ Prevention of unbalanced heat transfer in peak demands**		**47%**		

MS	Punctual discharge of heat to urban collectors (e.g. sewers)	33%
MO	**-Minimization of thermal shortcut (autointerference)**	**76%**
STGY	**▪ Adequate SGE systems design**	**78%**
MS	Hydrogeothermal characterization of the SGE systems domain	79%
MS	Thermal shortcut assessment during the licensing process	79%
MS	Assurance of correct emplacement of SGE systems boreholes	75%
MS	Licensing	72%
MO	**-Minimization of thermal interference between SGE systems**	**75%**
STGY	**▪ Reduction of unbalanced energy transfer of neighboring installations**	**73%**
MS	Operation temperature/flow rate threshold values	64%
MO	**-Efficient use SGE resources**	**74%**
STGY	**▪ Efficiency principle**	**69%**
MS	Thermal shortcut assessment during the licensing process	67%
MS	Maximize COPs of SGE systems	66%
MS	Licensing	64%
MS	Minimum COP exigible	63%
MS	Minimum energy quota related to the quote granted in the license	62%
MS	Mandatory thermal response tests	55%

PROB	**Inefficient use of geothermal resources**	**76%**
MO	**-Efficient use SGE resources**	**77%**
STGY	**▪ Efficiency principle**	**72%**
MS	Thermal shortcut assessment during the licensing process	71%
MS	Maximize COPs of SGE systems	70%
MS	Licensing	68%
MS	Minimum COP exigible	67%
MS	Minimum energy quota related to the quote granted in the license	66%
MS	Mandatory thermal response tests	60%

MANAGEMENT POLICY: ENVIRONMENTALLY FRIENDLY USE OF SGE RESOURCES

LEVEL	NAME	RELEVANCE [-]
PROB	**Activities raising threats to human health or the environment (general)**	**78%**
MO	**-Reduction of environmental impacts**	**80%**

STGY	**▪Precautionary measures**		**78%**		
MS	Leakage tests of the closed-loop refrigerant tubing	82%			
MS	Specific regulations on the heat carrier fluid type	76%			
MS	Evaluation and risk assessment during the licensing process	71%			
MS	Operation depth restrictions	71%			
MS	Boreholes sealing in decommissioning SGE systems	71%			
MS	Specific regulations on borehole heat exchanger grouting	70%			
MS	Licensing	70%			
MS	Tightness tests of the closed-loop refrigerant tubing	66%			
MS	Exact measurement of borehole depth of SGE systems	58%			
MS	Time-area closures	57%			
STGY	**▪Understanding how SGE exploitation impact the ecosystem function**		**73%**		
MS	Research and extension services	72%			
MO	**-Establishment of a cause and effect relationship for environmental impacts**			**79%**	
STGY	**▪Use of the best available science for decision-making**		**76%**		
MS	Monitoring and risk assessment throughout SGE exploitation	79%			
MS	Research and extension services	74%			
STGY	**▪Study of physical, biological and chemical processes triggered by SGE use**		**76%**		
MS	Research and extension services	77%			
MO	**-Identification of potential subsurface quality deterioration**			**77%**	
STGY	**▪ Environmental MSC system**		**76%**		
MS	MSC system for subsurface quality (groundwater)	79%			

PROB	**Contribution to Subsurface Urban Heat Island (SUHI) effect**				**56%**
MO	**-Prevention of a potential contribution to Subsurface Urban Heat Island effect in case of conflict**			**51%**	
STGY	**▪Control of SGES contribution to the SUHI effect**		**50%**		
MS	Mapping of city areas potentially harmed by SUHI	59%			
MS	Licensing	43%			
MS	Assessment of risks to human health/comfort or to the environment	39%			
MS	Time-area closures	28%			
MS	Operation depth restrictions	28%			

PROB	**Enhancement of existent microbiological contamination**				**55%**
MO	**-Prevention of the potential enhancement of microbiological contamination**			**55%**	
STGY	**▪Control of GE activities in microbiologically-contaminated areas**		**45%**		
MS	Licensing	51%			
MS	MSC system for subsurface quality (groundwater)	46%			

MS	Time-area closures	45%
MS	Mapping of microbiologically-contaminated areas in the city	42%
MS	Assessment of risks to human health or to the environment	41%
MS	Operation depth restrictions	35%

PROB	**Thermal groundwater discharge to hyporheic zone (exfiltration)**	**52%**
MO	**-Prevention of potentially negative environmental impacts on hiporreic zones**	**52%**
STGY	**▪Control of thermal groundwater discharge to surface water bodies**	**52%**
MS	Assessment of risks to the environment	56%
MS	Mapping of groundwater discharge areas in the city	48%
MS	MSC system for GW discharge to surface water bodies	46%
MS	Licensing	46%
MS	Time-area closures	37%
MS	Operation depth restrictions	32%

PROB	**Enhancement of existent (emergent) organic contamination**	**48%**
MO	**-Prevention of the potential enhancement of emergent organic contamination**	**48%**
STGY	**▪Control of SGE activities in emergent organic contamination areas**	**47%**
MS	Licensing	53%
MS	MSC system for subsurface quality (groundwater)	50%
MS	Time-area closures	46%
MS	Mapping of emergent organic contamination areas in the city	44%
MS	Assessment of risks to human health or to the environment	40%
MS	Operation depth restrictions	37%

PROB	**Enhancement of existent inorganic trace metals contamination**	**47%**
MO	**-Prevention of possible enhancement of inorganic trace metals contamination**	**51%**
STGY	**▪Control of SGE activi**	**51%**
MS	Mapping of areas in the city affected by trace metals contamination	59%
MS	Licensing	52%
MS	Time-area closures	50%
MS	MSC system for subsurface quality (groundwater)	48%
MS	Operation depth restrictions	46%
MS	Assessment of risks to human health or to the environment	43%

MANAGEMENT POLICY: SGE COORDINATION WITH OTHER URBAN SUBSURFACE USES

LEVEL	NAME	RELEVANCE [-]
PROB	**Groundwater quality as water supply**	**92%**
MO	**-Maintenance of groundwater quality standards**	**85%**
STGY	**▪Precautionary approach**	**81%**
MS	Protection of areas for drinking water supply (quality and quantity)	88%
MS	Groundwater management maps (priorization of use)	67%
PROB	**Groundwater use conflicts (irrigation, industrial, recreational, etc.)**	**84%**
PROB	**Urban subsurface use conflicts (general approach)**	**74%**
MO	**-Prevention/control of crosscutting conflicts**	**74%**
STGY	**▪Prevention and mitigation of crosscutting issues**	**75%**
MS	Inventory/mapping of other uses of urban subsurface	78%
MS	Licensing	71%
MS	MSC system in conflict areas	67%
MS	Depth restrictions	65%
MS	Time-area closures	48%
PROB	**Geotechnical impacts (subsidence)**	**61%**
MO	**-Prevention of fines migration into groundwater heat pump systems**	**69%**
STGY	**▪ Ensurance of laminar flow in extraction/injection wells**	**62%**
MS	Quality standards for well design, construction and maintenance	51%
MO	**-Prevention of dissolution subsidence**	**58%**
STGY	**▪ Groundwater isolation from atmospheric conditions**	**61%**
MS	Pressurized groundwater pipe lines and closed water reservoirs in SGE systems	75%
PROB	**SGE impacts on subsurface infrastructure**	**50%**
MO	**-Reduction of thermal impacts in tunnels (ventilation design)**	**39%**
STGY	**▪ Consideratio**	**41%**
MS	MSC systems near subsurface infrastructures sensible to temperature	37%
MS	Inventory/mapping of temperature-sensible subsurface infrastructures	36%
MS	Time-area closures	33%
MS	Licensing	32%
MS	Depth restrictions	21%

MANAGEMENT POLICY: SUCCESSFUL MANAGEMENT APPROACH

LEVEL	NAME	RELEVANCE [-]
PROB	**Managing in the context of data-poor urban subsurface body**	**83%**
MO	**- Providing an efficient management of SGE while improving a data-poor context**	**83%**
	▪ Improvement of the overall SGE data system	**83%**
MS	Reporting data	84%
MS	Assessment data	83%
MS	Data collection	82%
MS	Management data	82%
STGY	**▪ Simple management approaches (low information gathering)**	**83%**
STGY	**▪ Use of simple statistics to manage the SGE resources**	**82%**
STGY	**▪ Relying on the knowledge of SGE systems users**	**76%**
PROB	**Conflict of interest**	**82%**
PROB	**Inefficient management of the SGE resources**	**76%**
MO	**-Diminishing of enforcement problems and compliance**	**73%**
STGY	**▪ Providing legal certainty (economic stability)**	**72%**
MS	Licensing	70%
MS	Legal protection of rights/benefits	67%
STGY	**▪ Co-management approach**	**69%**
MS	Share of responsibility and authority for managing SGE resources	68%
MS	Sustained stakeholder participation through all planning and implementation phases	66%
STGY	**▪ Maximization of economic profits for SGE users**	**59%**
MS	Licensing	57%
MS	Guaranty of background/capitation temperatures of SGE systems	50%
STGY	**▪ Establishment of a SGE market**	**59%**
MS	Permanent or temporal transference of SGE rights	58%
MS	Inclusion of individual transferable quotas in the licensing process	58%
STGY	**▪ Adoption of a rights-based system**	**58%**
MS	Conferring certain rights to the user	59%
MS	Licensing	58%
MS	Long-term licenses (long-term user rights are granted)	58%
STGY	**▪ Increase of investments' security**	**51%**
MS	Licensing	52%
MS	Guaranty of background/capitation temperatures of SGE systems	43%
MO	**-Flexible iterative management approach**	**70%**
STGY	**▪ Adaptive management**	**68%**
MS	Standardized indicators for evaluating SGE management performance	68%

PROB	**Management measures dependence to site-specific conditions**				**75%**
MO	**-Adaptation of management measures to local boundary conditions**			**71%**	
STGY	**▪ Decentralization of SGE resources management**		**68%**		
MS	Shifting of responsibilities from central government to lower levels	59%			
MS	Rights-based system approach (Licensing)	59%			

PROB	**Disabling environment**				**72%**
MO	**- SGE capacity development (building)**			**73%**	
STGY	**▪ Development of appropriate policy and legal frameworks**		**80%**		
STGY	**▪ Capacity development is a requirement to institutional sustainability**		**68%**		
STGY	**▪ Development of institutions needed for sustainable SGE utilization**		**63%**		

PROB	**Uncertainty**				**68%**
MO	**-Coping with uncertainty**			**68%**	
STGY	**▪ Adaptive approach (adjustments and improvements mid-stream)**		**72%**		
MS	Program management cycle	74%			
STGY	**▪ Management measures applicable to a wide range of scenarios**		**59%**		
MS	Scenario assessment	65%			

PROB	**Illegal activity and heavy enforcement costs**				**53%**
MO	**-Implementation of an integrative and inclusive approach**			**58%**	
STGY	**▪ All the parties involved need a voice in the decision-making**		**61%**		
MS	Perceived benefit to stakeholders	64%			
MS	Adaption of the planning, decision-making and implementation process	61%			
STGY	**▪ Ensuring an inclusive and participatory approach**		**58%**		
MS	Stakeholder mapping	56%			
MS	Sustained stakeholder participation through all planning and implementation phases	56%			
MS	Vulnerability and capacity analysis	53%			
MS	Avoidance command and control actions (are costly and ineffective)	43%			
STGY	**▪ Co-management approach**		**61%**		
MS	Assessment of existing capacity of enforcement	63%			
MS	Stakeholders involvement in the decision-making process during the planning and implementation phases	59%			
MS	Assessment of existing capacity of stewardship development	58%			
MS	Co-management approach	57%			

Supplementary Material

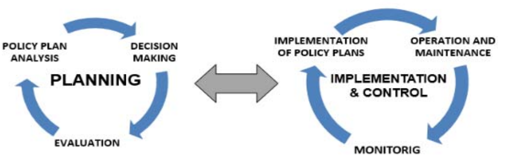
Governance of shallow geothermal energy resources

Alejandro García-Gil, Gregor Goetzl, Maciej R. Kłonowski, Staša Borovic, David P. Boon, Corinna Abesser, Mitja Janza, Ignasi Herms, Estelle Petitclerc, Mikael Erlström, Jan Holecek, Taly Hunter, Vincent P. Vandeweijer, Radovan Cernak, Miguel Mejías Moreno and Jannis Epting

May 29, 2019

Table S2. Complete results obtained from survey on governance of SGE resources.

Governance of shallow geothermal energy resources

SGE MANAGEMENT APPROACH	**Adaptive management approach**	**82%**
	Learning process: Monitoring + evaluation → iterative adjustments	81%
	Definition of management indicators linked to project goals and objectives	74%
	Intensive management data collection → Management indicators	67%
	Planning-implementation-control relationship cyclical/iterative	70%
	The management cycle 	73%

PLANNING

POLICY PLAN ANALYSIS	**Problem identification & assessment:**	**Knowledge on the local context of SGE systems:**	**84%**
		-Current status and trends of the SGE resources	85%
		-Origin of heating and cooling demand	74%
		-Key drivers of changes in the local context	70%
		-Existing governance structure and management rules	78%
		-Types of SGE systems involved	79%
		-Exploitation regimes of SGES systems	74%
		-Crosscutting issues of subsurface urban environment	78%
		-Identification of conflict areas between SGE systems	83%
		-Identification of the relationships between SGE users	74%
		-Hydrogeothermal characterization of the shallow urban subsurface	81%
		Examination of different angles to understand SGE systems:	**67%**
		-Kinds of buildings using SGE	61%
		-Heating capacity of systems (order of magnitude)	66%
		-Importance of using SGE for the systems	60%
		-Legal frameworks affecting them	69%
		SGE resources assessment: (*status of resources to be managed*)	**84%**
		-Provide past and current status of SGE resources:	82%
		▪ Overexploited current extent	79%
		▪ Overexploited extent evolution over time	75%
		▪ Potential future trends of the overexploited extent	76%
		-Prediction of SGE resources respond to future management actions	74%
		-Management risks (probability that a measure will not achieve its goal)	61%
		-Selection of the best options for future management (learning process)	63%
		-Resource assessments linkage to scenario of reference:	56%
		▪Reference scenario explaining management objective	51%
		▪Indicator of the status of a desired SGE resource status	64%
		▪Indicator of the status of min/max condition scenario	60%
		Socioeconomic assessment: (human dimensions of SGE exploitation)	**58%**
		-Performance in meeting social goals	54%
		-Performance in meeting economic goals	65%
		-Proposed regulations impact on SGE users	58%
		-Socioeconomic information requirements:	55%
		▪Physical geography of the urban area managed	64%
		▪Settlement patterns and SGE users trends	61%
		▪Nature of the socioeconomic activities of SGES	60%
		▪Maintenance costs of SGE systems	65%
		▪SGE systems location and infrastructure associated *(e.g. wells location, heat exchangers location)*	70%
		▪Types of heat pumps, heat exchangers, etc	57%
		▪Data on who is controlling the system *(own maintenance personnel, private company, etc)*	60%
		▪Perceptions and role of the SGE stakeholders: *(concerning issues and problems)*	60%
		▫Trends in the conditions of the SGE resources	56%
		▫Legitimacy of regulations	57%
		▫Degree of compliance with rules	50%
		▫Prevalence of use of illegal practices	49%
	Establishment of management objectives	-Management objectives should be clearly defined	80%
		-Management objectives should be directly linked to activities	77%
		-Objectives should be specific, measurable, achievable, realistic and time-related	79%
		-Objectives should be established through a participatory process	64%
		-Objectives establishment should consist in a transparent process based on the best available science and socioeconomic impact assessment	75%
		-Each management measure should list its objectives and outcomes	78%
	Identification of possible strategies and measures	**Identifcation of priorities upon which to focus effort and resources:**	**73%**
		-Identification of systems to be acted upon resource constrains	72%
		-Identification of systems to be acted upon institutional constrains	51%
		-Identification of systems to be acted upon technical constrains	61%
		-Program priorities selection involving users and decision-makers	63%
		- Identification and involvement of institutions interested in SGE resources	69%
		- Solicitation of the point of view of stakeholders and the general public (if possible)	56%
		- Identification of potential leaders and stakeholders representatives that will be involved in the implementation of the program	68%
		- The scope and complexity of management priorities corresponds to the capacity of the institutions involved	69%
		General categories of activities to achieve SGE management goals:	**77%**
		-Policy reform	65%
		▪Enabling environment (mix of policies + law + regulations)	69%
		▪ Establishment of the degrees of co-management	60%
		▪ Establishment of the degrees of decentralization	43%
		▪ Implementation of rights-based SGE management regimes	60%
		-Planning site-based SGE management plans:	78%
		▪ Management plans for specific urban conditions	80%
		▪ Adaptation of management strategies to site-based locations	80%
		▪ Proposing local site-based management initiatives (pilots)	71%
		-Capacity development and training	66%
		▪ Strengthening technical capacities of local SGE scientists to conduct SGE resource assessments	80%
		▪ Engaging stakeholders in a participatory and sustainable process	78%
		▪ Targeted at government agencies, resource users and other stakeholders groups	80%
		Design of different options (alternatives for measures adopted)	**50%**
		Impact assessment of each management measure option	**45%**
		Thorough evaluation of the options (weighing “pros” and “cons”)	**63%**
DECISION MAKING		**Stakeholder participation:**	78%
		-All interests need a voice in the decision-making	60%
		-Measures must be widely accepted by stakeholders	73%
		-Participation must be sustained during all phases	70%
EVALUATION & ADAPTIVE MANAGEMENT		-Evaluation of the effectiveness of management measures	54%
		-Standardized indicators for evaluating the performance of the management	53%
		-Evaluation based on indicators directly linked to management goals	53%
		-Intensive data collection longer than measures application period	51%
		-Evaluation for adaptive management (learning)	64%
		-Decisions/actions adjusted to heating/cooling season beginning	64%

IMPLEMENTATION & CONTROL

IMPLEMENTATION OF POLICY PLANS	**Elaboration of a detailed design of planned measures**	**66%**
	Elaboration of a detailed plan for the implementation of planed measures	**65%**
	Enforcement of laws and regulations	**65%**
	Strengthening the enabling environment and governance to prevent:	**74%**
	-Conflicts of interest	77%
	-Inadequate management resources (physical and financial)	68%
	-Poor enforcement	68%
	-Illegal SGE systems exploitation	57%
	-Lack of stakeholders participation in decision-making	69%
	-Lack of clear vision	69%
	-Users conflicts	71%
	-Failure to control SGE systems	65%
	Incorporation of a precautionary approach	**74%**
	-Minimization of the risk by implementing the “precautionary approach”	77%
	-Dealing with uncertainties associated to:	75%
	▪ SGE resources assessment	77%
	▪ SGE use impacts on the resources	77%
	▪ SGE use impacts on the environment	74%
	- Precautionary approach implementation to:	69%
	▪ Uncertainties related to the total heat transfer rates of SGES	69%
	▪ Reference scenarios in general	71%
	▪ Resources status in relation to reference scenarios	69%
	▪ Levels and spatial distribution of SGE resource loss	68%
	▪ Impact of SGE systems (SGE resources/environment)	81%
	▪ Environmental and economic conditions	81%
	Implementation in the context of data-poor environments	**82%**
	- Specific management approach to data-poor systems:	77%
	▪ Use of simple statistics to manage the SGE resources	83%
	▪ Rely on the knowledge of SGES users	71%
	▪ Use of simple management approaches	77%
	- Managers should improve overall SGE data system:	80%
	▪ Data collection	82%
	▪ Management data	77%
	▪ Assessment data	77%
	▪ Reporting data	80%
	Program adoption and funding:	**66%**
	- Formal adoption of management plans for full legal/political legitimacy	58%
	- Enforcement and penalties imposition to violations	57%
	- Implementation of programs in the form of a management committee	61%
	- Management committee carrying out management function (monitoring, surveillance and enforcement)	60%
	- Management committee responsible for periodically revising/updating the plan to meet the objectives	61%
	- Formal adoption to make funding available to the management agency or a co-management committee	47%
	- Authority collection of licensing fees for SGE exploitation rights	65%
MONITORING	**Monitoring, control and surveillance**	**78%**
	- Enabling compliance through instrumental measures (MCS system)	78%
	- MCS system chosen in function of the SGE sector managed structure	72%
	- Setting a MCS strategy:	78%
	▪ Type of SGE systems: residential, industrial, open, closed, horizontal	71%
	▪ Type of management measure	79%
	▪ Legal framework: Energy/geology acts, regulations and rules	80%
	▪ Human resources: qualified personnel responsible for the MCS system	60%
	▪ Time dimension: before/during/after SGE exploitation/remediation	72%
	▪ Financial requirements: cost effectiveness, payer, low-cost options	83%
	- Co-management allows:	64%
	▪ Users responsible for research and monitoring activities	70%
	▪ Users’ expertise incorporation into management models	68%
	Monitoring of effectiveness	**72%**
	-Developing systems to monitor impacts of management activities planed	76%