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Review

Assessment of submarine geothermal resources and development of tools to quantify their energy potentials for environmentally sustainable development

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ABSTRACT

Submarine geothermal reservoirs contain huge amounts of energy, not been used so far but recently considered for exploitation. Their energy potentials are much larger than those of onshore geothermal resources and can cover significant parts of the global future energy demands in an environmentally sustainable way. There are two types: (i) deep resources along oceanic spreading centers, where uprising magma heats fluids circulating through fissured rocks, which emerge at vents at temperatures up to 460 °C, mixing with seawater (depth: 1000–4000 m below sea level), and (ii) coastal shallow resources where geothermal fluids emerge at fractures (depth: 1–50 m). The total length of deep systems is ~65,000 km and there are sites where pressure and temperature are high enough that they are at supercritical conditions. The first part of this paper assesses global information on submarine geothermal resources, concluding that – using mature technology from onshore geothermal and offshore hydrocarbon exploitation – submarine geothermal resources can be an economical affordable option for energy supplies at small-large scale. In the second part a – generally valid – robust, mathematical approach is developed to quantify these resources and its applicability is demonstrated using two examples. In Baja California (Mexico), the coastal submarine geothermal potential per cubic kilometer of rock of Punta Banda, Wagner Depression and Gulf of California resulted 245, 350 and 528 MW_T/km^3, respectively. Transforming only 1% of this energy into electricity the capacity of the Gulf of California alone is ~26,000 MW_e. The submarine geothermal system of Santorini Caldera (Greece) yielded 869 MW_e (reservoir 100 km^3).

1. Sustainable energy for all – an introduction

Global energy demand is expected to double in the next two decades (IEA, 2012). At the same time, scarcity of fossil fuels, which are still the globally dominating energy source, is increasing. The oil peak production is already exceeded and it is forecasted that oil production from conventional sources will decline by 2030 to 50% of the 2010 production (EWG, 2007) resulting in increasing fossil fuel prices and uncertainty of supply. Securing the provision of increasingly large amounts of energy at economically affordable prices (on global and regional levels), while simultaneously avoiding greenhouse gas emissions that would occur if the additional energy demand would be covered by fossil fuels – the primary contributor to global warming – e.g. by increased use of renewable energies, is therefore crucial in a world facing both population and economic growth.

Making environmentally sustainable choices, which can provide the people for their energy needs, is therefore essential. This is valid for developed and developing countries; the special need for the last group becomes evident when considering that in the year 2012 approximately 1.4 billion people (i.e. ~17% of the world's population) had no access to electricity (GEA, 2012) and 2.8 billion people used traditional fuels (wood, charcoal, and animal and crop waste) to prepare food and heat their homes (The Economist, 2013). Energy demand increases are particularly high in developing

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Nomenclature

Symbols

c_p	isobaric specific heat capacity [J/kg/K]
c_r	rock specific heat [J/kg/°C]
c_w	water specific heat [J/kg/K]
η	geothermal-electricity conversion factor [-]
f_E	coefficient of recoverable electr. energy [-]
G_p	electric geothermal power [MW_e]
H_G	geothermal energy [J]
k_T	thermal conductivity [W/m/°C]
MW_e	Megawatt electric
MW_T	Megawatt thermal
p	fluid pressure [Pa, bar]
q	heat flow [W/m^2]
Q_H	power of the heat source [W/m^3]
ρ	density [kg/m^3]
ρ_R	rock density [kg/m^3]
t	time [s]
t_A	pay-off time of the geothermal project
t_E	period of commercial exploitation
T	temperature [°C]
V_R	rock volume (reservoir volume) [m^3]
Z	height of the plume
z	vertical (depth) coordinate

countries and countries in transition where population growth is highest and where economies and therefore living standard grow fastest. For example in the case of electricity, the world-average demand is forecasted to increase by 70% in the 2010-2035 period (on average 2.2% per year); with a much higher average annual growth rate in developing countries (3.3%) compared to industrialized countries (0.9%) when using the New Policies Scenario (IEA, 2012). To address the challenges resulting from these forecasts, United Nations secretary-general Ban Ki-moon, who sees energy as "the golden thread that connects economic growth, social equity, and environmental sustainability", launched the UN initiative "Sustainable Energy for All" in 2009 (Detchon and Van Leeuwen, 2014). This initiative has three goals to accomplish until 2030: (i) universal access to modern energy services; (ii) doubling the global rate of improvement in energy efficiency; and (iii) doubling the share of renewables in the global energy mix (Detchon and Van Leeuwen, 2014).

In many cases, renewable energy, which is locally available is an environmentally sustainable and technical and economical viable alternative of traditional fuels for industrial, agricultural and domestic applications in developed but also in developing countries where it can improve rural electrification and assist the poor to meet their needs for access to heat, light, and refrigeration. It is well-known that renewable energy sources – when compared to fossil fuel based fuels – have huge benefits as they are locally available, increase the independence of fossil fuel markets and energy security, lead to added benefits that stimulate local employment, contribute to improve living conditions, enhance economic opportunities and so regional development, reduce the migration of the rural population into the cities and reduce indoor air pollution resulting from cooking with coal or wood, which has resulted in annually nearly two million casualties through pneumonia and chronic lung disease. At the same time they are contributing to a reduction of greenhouse gas emissions from energy use that amount about 65% of the global greenhouse gas emissions. (Dixon et al., 2011; IEA, 2012; UNDP, 2009).

The advantages of renewable energy technologies are very variable and depend principally on the type of fossil-fuel based power generation which they replace. This has been shown by an evaluation of existing conventional power generation facilities across the USA and the analysis of the impacts that would occur if they would be replaced by wind and solar powered facilities; this study found vary variable but significant social and environmental benefits (Siler-Evans et al., 2013).

When looking on the renewable energy options, it becomes evident that geothermal (onshore and offshore) has a key benefit when compared with wind and solar: Geothermal energy provides a constant, stable energy source (in contrast to solar, wind and hydropower) and requires therefore no expensive energy storage and further allows up-scaling to very large-scale facilities, which is not currently possible with solar and wind. The draw-back of the geothermal option is – equally for onshore and offshore – the high exploration risk (investment risk) and the high installation cost, which however will be later off-set by electricity generation cost below of these from solar, wind and hydropower plants, as proven for onshore geothermal plants. The exploitation of onshore hydrothermal geothermal systems is a mature technology and it is economical competitive (or cheaper) not only when compared with other renewables but also regarding fossil fuel power plants, in particular, if all relevant factors such as internalization of environmental damage into the price of power produced from fossil fuels is considered (Fig. 1).

Submarine, offshore geothermal energy, the potential of which is larger than those of onshore geothermal resources, is one of the renewable energy sources, which have not been considered in the past decades as an economical and technological feasible option. However, they are able to replace advantageously fossil fuels and form a choice which becomes increasingly more attractive as manifested by several new research and an increasing number of publications related to this emerging topic (e.g. Kárason, 2013; Armani and Paltrinieri, 2013). This non use of offshore geothermal sources is despite the fact that there are a significant number of studies and that the successful use of onshore geothermal facilities for power generation has been proven in 21 countries the economic and technical sustainability of geothermal power generation and its contribution to regional development. These studies found beneficial development impacts and proved that opportunities for geothermal projects exist in many areas of the developed but also in developing and transition countries where geothermal power plants of different scale could supply electricity, where it is most needed: in remote areas or underdeveloped regions (Dixon et al., 2011; Vimmerstedt, 2002).

In the first part of this paper, we reviewed the current scientific literature regarding submarine geothermal resources and their potential uses. We evaluated the relevant international journal publications available on-line, in particular those of the last 10 last years but also reports, with two central purposes: to trace the outline of the fundamental characteristics of submarine hydrothermal reservoirs on global scale and options and ongoing research regarding their exploitation. In the second part, we develop an innovative, robust, and general valid mathematical approach for basic characterization analysis of the main characteristics and determination of the potentials of this enormous energy source that has never been used on earth. We illustrated the applicability of this mathematical approach by introducing preliminary evaluations of the Gulf of California, Mexico and of