Concepts for Sustainable Geothermal Energy Development in Remote Geothermal Areas of Indonesia

K. Erbas[1], M. Jaya[1], I. Moeck[1], F. Deon[1], M. Brehme[1], S. Regenspurg, [1] S. Frick[1], S. Kranz[1], R. Bäßler[2], E. Huenges[1]

[1]Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany
[2]Federal Institute for Materials Research and Testing, Berlin, Germany
kemal.erbas@gfz-potsdam.de • http://www.gfz-potsdam.de/ICGR

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Introduction

The republic of Indonesia is composed of many islands and widely extended. Nowadays, the state with the fourth highest population worldwide has to solve a giant demand on food and energy. Existing resources of oil and gas are limited in Indonesia and the existing infrastructure to reach the customers of the energy is not sufficient, as access to many areas in Indonesia is limited. Therefore, de-central, location adapted energy provision is crucial. One third of the Indonesian population has no access to the electricity grid and about 45000 smaller gasoil fired power plants (diesel generators) are operating far of the power grid (ESDM 2009). These plants have no future due to decreasing access to gas and oil and increasing costs for this energy carrier. Renewable energy can contribute to the provision of energy in remote areas. Geothermal is one of these and has huge resources in Indonesia. Today, geothermal provides ~1.2 GW_e electrical capacity that represents only a small part of the identified potential. The Indonesian government plans an extension of the deployment of geothermal electricity until 2025 to 9.5 GW_e that represents a significant part of the estimated resources of 27 GW_e (Surya Darma et al, 2010).

However, there is a gap in reliable technologies for solutions to provide de-central geothermal energy. In addition, human resources respectively engineers are missing to handle the extension of the capacity. Indonesian studies indicate the requirement of 50-70 well-educated geothermal engineers for each additional 1000 MW_e installed capacity (Saptadji, 2010). Further development of geothermal technology is as important as capacity building. Recently a German-Indonesian cooperation started with the project "Sustainability concepts for exploitation of geothermal reservoirs in Indonesia – capacity building and methodologies for site deployment" in order to find site-specific technical solutions and to support the required education in Indonesia. In this context, a PhD-program was initiated and installed to support these goals.

First reservoir engineering field studies conducted in the fall of 2010 yield further boundary conditions for plant optimization and adaptation for possible locations in Indonesia. A currently ongoing comprehensive exploration program focuses partly on low enthalpy geothermal "green fields" in magmatic and amagmatic settings to further elaborate potential sites on Java, Sumatra, and Sulawesi for future deployment (Fig. 1).

Figure 1. Potential sites for starting German-Indonesian Cooperation.

A prototype ORC module for geothermal power generation from low enthalpy fields that was presented by the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences at the WGC 2010 in Bali, will be adjusted and optimized for such areas.

Factors of Deployment

It is difficult to predict future rates of deployment, because of numerous variables involved (Huenges, 2010). With the present engineering solutions, an increase from the current value to 10 GW_e installed capacity in Indonesia should be achievable. The gradual introduction of new technology improvements is expected to boost the growth rate. In addition to large-scale power plants other core technologies (for example, small-scale binary plants) are entering the field demonstration phases to prove commercial viability.

Low temperature power generation with binary plants opened up the possibilities of producing electricity in areas that do not have high temperature resources and thus give an opportunity for many remote areas. If these technologies can be proven economical at commercial scales, the geothermal market potential will be limited only by the size of the grid or the total demand.

Economic and Political Factors

Utilization of geothermal resources varies from being nearly site-independent (EGS in mostly dry environments in mainly non-volcanic areas) to site-specific (for hydrothermal sources). The distance between electricity markets or centers of heat demand and geothermal resources is a factor in the economics of power generation.

When making development choices, there is sometimes a trade-off between the quality of hydrothermal resources and their remoteness from secure grid connections or demand centers. The renewable, reliable, and cost-competitive nature of geothermal energy has attracted some energy-intensive industries (e.g., aluminum smelting, pulp and paper, timber drying) to collocate with geothermal resources to attain a comparative commercial advantage. In the context of mandates for increased use of renewable energy and for reductions of green house gas emissions, this collocation trend is expected to increase.

The deployment of all technologies relies on the availability of skilled installation and service companies. For deep geothermal drilling and reservoir management, such services tend to be concentrated in a few countries only. Larger deployment is generally facilitated by establishing insurances to cover drilling, development, and production risks. Therefore, project risk management is another requirement for financing, installing, and operating large geothermal installations. Prior knowledge and expertise within the local banking and insurance industries generally assist in accelerating local deployment rates.

Geothermal deployment will also be supported, politically, by a CO_2-mitigation strategy, through establishing incentives for market penetration of geothermal energy supply technologies. These incentives can include, for example, subsidies, guarantees, and tax write-offs to cover the risks of initial deep drilling. Policies to attract energy-intensive industries (e.g., aluminum smelting) to known geothermal resource areas can also be useful. Feed-in tariffs with confirmed geothermal prices have been very successful in attracting commercial investment in some countries (e.g., Germany).

Policy support for research and development is required for all geothermal technologies. Public investment in geothermal research drilling programs should lead to a significant acceleration of geothermal deployment.

Support is also needed for programs to educate and enhance public acceptance of geothermal energy use, and to conduct research toward the avoidance or mitigation of potential induced hazards and adverse effects.

Capacity Building

One of the limiting factors for the growth of geothermal energy supply in Indonesia is the availability of qualified human resources. To help overcome this limitation the Indonesian-German cooperation project supports initiatives to expand geothermal training in Indonesia. A number of initiatives are ongoing and planned: Indonesian-German expert exchange program; PhD program with several PhD positions in Exploration, Reservoir Engineering and Geothermal Plant Technology supervised in Germany¸ GFZ experts will participate in a teaching program at Indonesian partner institutions.

Controlling Technology Factors

Geothermal power generation technologies have different degrees of maturity. The deployment conception has to strengthen the weak points of the existing technologies in Indonesia. Reducing subsurface exploration risks will contribute to more efficient and sustainable development in Indonesia. The drilling of high temperature reservoirs requires advanced technologies to prevent reservoir damage by drilling mud; an example is the use of balanced drilling procedures. Higher utilization efficiency requires improved performance of surface installations and a special focus on the auxiliary energy demand. Better reservoir management, with improved simulation models, will optimize reinjection strategy, avoid excessive depletion, and plan future make-up well requirements, to achieve sustainable production.

The quality of the heat extracted, and its potential diversity of use, increases with heat source temperature. Improvements in total energy efficiency from cascaded use of geothermal heat are an important deployment strategy. Evaluating the performance of geothermal plants, including heat and power installations, will consider the temperature level of the geothermal heat by differentiating between energy and exergy content (the part of the energy that can be converted to power).

Technology Approaches

Exploration

Indonesia is located at the Sunda-Trench representing the subduction zone of the Indo-Australian and the Eurasian Plates. The collision between these plates is oblique along Sumatra and frontal along Java and eastwards. The volcanic arc setting along the subduction zone hosts abundant geothermal systems. However, there are not only magmatic systems but also amagmatic geothermal systems especially in fault-controlled regions, for example the NW-SE striking Sumatra fault zone. Many geothermal manifestations such as hot springs, travertine, and argillitic alteration evidence the geothermal activity and are generally target locations for geothermal site development. There might be, however, many more geothermal systems that are hidden. The aim of an extensive exploration study on North-Sumatra (Tarutung Basin) and East-Java (Mount Lamongan) shall help to characterize geothermal systems of both types, structurally controlled and magmatic controlled.

To establish if a region is suitable for geothermal purposes one has to perform detailed fieldwork followed by geologic-petrologic-structural studies. These observations are basic to achieve reliable information for evaluating a region as candidate for geothermal applications. A suite of different methods and techniques is required to image and characterize hidden geothermal systems in high enthalpy regions.

Geology

Sipoholon – North Sumatra: Example for Exploration in an Amagmatic Setting

The Tarutung Basin developed along the NW-striking dextral strike slip Sumatra fault and is located about 50 km southeast of the prominent Lake Toba caldera. The basin lies in a right step over region along segments of the Sumatra fault indicating a pull-apart basin. The stratigraphic section of the Tarutung Basin consists nearly entirely of Tertiary to Holocene volcanic and volcanoclastic strata that complexly interfinger. The rocks consist of Tertiary lava flows, lahar deposits, and tuffs derived from the more distant volcanic centers such as the Toba Caldera (Hickman et al., 2004). Massive travertine deposits in the NE of the Tarutung Basin near Sipoholon and associated hot springs evidence discharge of a geothermal system. During a first field geology campaign more travertine deposits were found aligned along strands of the Sumatra fault. Obviously, the travertine deposits and hot springs with high flow rates are concentrated along the eastern part of the basin. Different generations of travertine deposit occur most likely in the NE area of the Tarutung basin, and were systematically sampled to perform future geochemical dating. In particular, ^{234}Th/ ^{238}U geochemical dating shall be used if the chemical information from the EMPA (Electron Mircroprobe Analysis) results not sufficient to distinguish the different travertine generations. The knowledge of the travertine age represents a fundamental milestone to understand the tectonic and geological time scale of the Tarutung basin formation and its geothermal activity.

Tiris – East Java: Example for Exploration in a Magmatic Setting

The province of Java Timur represents a challenging region for geothermal exploration in a magmatic scenario. The volcano Lamongan - Tiris belongs to the Sunda Arc Region (tectonically active area - extensional regime).

We collected samples in locations spread W and E of the mount Lamongan and examined them with a systematic approach. In the field we could observe two main deposits: lava flows (sign of a quiet effusive activity) and pyroclastic flows, originated by more violent and explosive episodes. The lava outcrops showed interesting radial structures indicating rapid cooling and contact with ground water. The pyroclastic deposits originated either from a phreatic or phreato-magmatic eruption: both manifestations implicate the contact between magma with ground or hydrothermal (relatively hot with temperature of 60-70°C) waters. Our approach with several analytical techniques (XRD (X-Ray powder diffraction), EMP (Electron Microprobe), and SEM (Scanning Electron Microscope)) aims to provide a detailed analysis of these rocks, in order to understand if they are suitable to act as reservoir rocks. A key point of the measurements is represented by the XRD pattern of the rock samples: refining the phase assemblage one can obtain density of every single mineral constituent, which is fundamental for planned porosity - permeability measurements. The first results indicate that the major occurring effusive lava (FD1) is an andesite (An) containing 70 wt. % of labradorite $Na_{(0.1)}Ca_{(0.67)}Al_{(2.58)}Si_{(1.71)}O_8$, 20 wt. % of quartz and 10 wt % Fe-Mg minerals (olivine and diopside - Ca pyroxene), all occurring as pheno-crystals. We observed a second lava FD8 suite where on the one hand the composition of plagioclase remains basically constant $Na_{(0.35)}Ca_{(0.65)}Al_{(2.45)}Si_{(2.36)}O_8$ on the other hand the glomero-crystals (crystal wider than 1.5 mm) present interesting chemical Ca zoning and the content of olivine and Ca pyroxene is higher (Fig. 2a and 2b). This could imply a chemical exchange (Ca) between plagioclase and the melt: such exothermic reactions are very important. They produce indeed, even if only locally, a considerable amount of heat over a short period (10^2-10^4 years). Density (of the rock-mineral), permeability, porosity measurements along with detailed petrologic-mineralogical analyses are the major tool to evaluate the possibility for these rock bodies to act as reservoir rocks. In a second field campaign in May 2011, investigation area has been enlarged to the Iyang-Argopuro Volcano, in order to deepen the understanding of the heat sources in the investigated region.

Geophysics

Magnetotellurics

Electrical conductivity is a key parameter for the exploration of geothermal reservoirs, especially in volcanic areas where clay alteration minerals surrounding the reservoir present a strong conductivity background. Magnetotellurics (MT) has been widely used in geothermal sites throughout the world. MT can provide electrical conductivity models from the near surface down to depths of several kilometers. Methods involve field experiments (starting in summer 2011), data processing and 2D/3D modeling of conductivity distribution. Resulting MT models can be integrated with other geophysical and geological data to produce conceptual reservoir models.

Seismology

We focus on natural micro- to local-scale seismicity to characterize subsurface active faults and stress state of geothermal fields. A six-month observation period with 40 seismic stations was started at the beginning of May 2011 in Northern Sumatra (Tarutung Basin). The interpretation methods involve advanced data analysis and modeling/inversion of P and P-/S-velocity and attenuation using tomography methods. Integrated interpretation of different results from the passive seismology study and further data (structural geology, MT and others) will thus improve the understanding of geothermal systems, particularly the prediction of fault zones that control heat transfer or fluid flow.

Seismics

Reflection seismic techniques are a key technology for reconnaissance studies for exploration wells. In areas with high geothermal gradients, high-resolution seismic investigations open a new field of application, which has only recently gained some importance in correlation with exploration wells. A geological-geotechnical evaluation of selected sites will lead to specific reflection seismic campaigns and multi component acquisition techniques will be developed. Effectively, a site-specific workflow can be developed for high-resolution reflection seismic employing 2D/3D techniques to image the structural pattern of geothermal fields. A first field campaign in North Sumatra started in May 2011 yielded valuable information for setup of low-energy (vibrator) sources and geophones for shallow structural investigations.

Reservoir Engineering and Modelling

Reservoir engineering is essential for an appropriate development of geothermal resources. Optimum economic utilization of geothermal reservoirs requires analysis of the geological system together with adequate planning. These include chemical and petrophysical reservoir characterisation, reservoir stimulation and modelling as well as understanding of the processes and interaction of the borehole-reservoir system.

An appropriate numerical model is important for planning the well path and fracture design, interpreting hydraulic tests and stimulations, and predicting reservoir behaviour during geothermal power production. Such models should include: (i) the reservoir geology and structure, (ii) the geometry of wells and fractures and (iii) the hydraulic, thermal, mechanical and chemical (HTMC) conditions of the reservoir and fractures generated due to changes in reservoir conditions.

In November 2010 a geothermal site (Lahendong, Sulawesi) was visited and available hydraulic, geological, and hydrochemical properties were reviewed. Additionally, water samples from production wells, nearby hot springs, and a lake have been taken and analysed. At this location, several wells are drilled into three sub-reservoirs of different fluid composition, located at different depths with temperatures between 250 and 350 °C (Fig. 2). All of them provide steam for electricity production.

The temperatures as well as the hydro-chemical characteristics vary: The deepest reservoir with a moderate pH is marked by high silica and chloride concentrations. The fluid in the shallowest reservoir above is highly acidic. Still higher chloride, silica, and sulphate concentrations appear in this reservoir. Acid water was also observed in a nearby lake indicating a hydraulic connection to the shallow reservoir. The hydraulic and hydro-chemical connection between these different surface and subsurface reservoirs should be explained through an integrated model. Ultimately, the permeability anisotropy can be analysed by these integrative flow simulation models considering hydraulically active domains in porous rock as well as faults and fractures.. A hydro-chemical transport model (PhreeqC) will explain water-mixing processes and the effect of geology on the fluid characteristics.

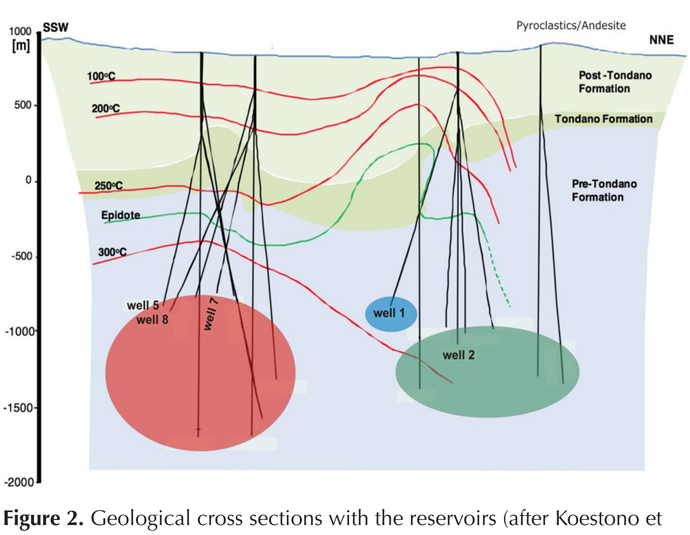

Figure 2. Geological cross sections with the reservoirs (after Koestono et al. 2010).

Stimulation

Stimulation treatments are an option to enhance the productivity of low permeability geothermal reservoirs by inducing artificial fluid pathways. At GFZ specific stimulation treatments have been developed to enhance the existing permeability; i.e. hydraulic fracturing, thermally induced fracturing and chemical/acid stimulation. In hydraulic stimulation experiments, fluids are injected under high pressure into the subsurface rocks to create new fractures or extend existing fractures.

Rock Physics

Effective energy production from geothermal reservoirs requires the characterization of the physical properties of the host rock as precisely as possible. Additionally, rock physical experiments provide a valuable complementary method to investigate particular processes associated with mechanical and thermodynamic changes induced during operation. The results of such investigations improve the outcome of hydro-thermo-mechanical-chemical (HTMC) simulation codes in order to derive statements on reservoir productivity, sustainability, and best-practice operation.

Geochemistry in Exploration

The chemical composition and physical properties of geothermal fluids, measured in geothermal manifestations such as hot springs can give important information about reservoir characteristics such as its temperature (geothermometer) or geologic origin and pathways of the fluid to the surface. Therefore, geochemistry is an important tool for geothermal exploration. Geothermal fluids of the geothermal areas Tiris (East Java) and Sipoholon (North Sumatra) have been analyzed in-situ and fluid samples have been collected (Fig. 3) and analyzed by standard field and lab methods.

It was found, that the four known geothermal brines in Tiris can be classified as Mg-Cl-HCO_3 waters indicating a location at the margin of the geothermal system and mixing with meteoric water, which causes difficulties in the application of geothermometers. However, most realistic reservoir temperature according to SiO_2 geothermometers is about 190 °C. In Sipoholon, about 20 manifestations have been sampled and analyzed revealing more

Figure 3. Sampling a hot spring at Tiris, East Java.

detailed properties of the reservoir consisting of both sulfate, and bicarbonate waters.

Geothermal Plant Technology

The goal of the Indonesian government, to increase sustainable geothermal exploitation within the next decade, can only be achieved by developing innovative plant concepts. Efficient and reliable plant technology considers the specific preconditions and requirements of a site where production and injection wells shall be installed to maintain sustainable conditions in the reservoir. Main challenges refer to plant efficiency and geothermal fluid loop optimisation, geochemical issues, infrastructure integration, and ambient conditions.

Corrosion and Scaling

During the operation of a geothermal plant,chemical reactions between the geothermal fluid and either the reservoir rocks (during fluid re-injection) or the plant components can occur and damage both, the reservoir by clogging the pores and the plant materials by corrosion and scaling. Therefore, understanding the geochemical reactions helps evaluating potential risks during plant operation. Geochemical processes, relevant for geothermal energy production at Indonesian sites are investigated at the field and the lab scales.

For the installation of a binary plant at a geothermal site in Northern Sumatra (see below) it has been calculated that silica will be highly oversaturated at fluid temperatures after cooling down in heat exchangers (< 100 °C). Therefore, pre-experiments are performed to assess silica scale formation after heat extraction and fluid re-injection into the reservoir. To develop a method for quick removal of silica from the brine, a field experiment is setup studying silica polymerization and precipitation at various temperatures and by addition of scale accelerating components. Additional lab experiments focus on silica formation processes induced by changes in p-T-conditions in synthetic brines.

Many components in geothermal fluids are highly reactive and can cause serious damage to the plant materials. Exact knowledge on the behaviour of installed plant materials depending on fluid chemistry, as well as of the temperature, pressure and flow conditions is essential in order to prevent corrosion, reduce material costs and increase reliability of components (Bäßler et al. 2009). The effects of these parameters on suitable materials in laboratory and in-situ field experiments are investigated. In order to have reliable results, classical exposure tests and electrochemical measurements will be performed both in the laboratory and at the test site in Northern Sumatra in real conditions. It is planned to have a corrosion test rack installed in collaboration with the owner of the site (PGE).

Energy Supply

Deep geothermal heat can be used for heat, electricity and chill supply. The engineering of geothermal systems is based on conventional engineering approaches that need to be adapted and enhanced according to the specific geological, infrastructure and ambient preconditions at a site (Saadat et al. 2010b). Our work at GFZ focuses on the adjustment of existing, proven components for an integration in new configurations. In collaboration with different partners experienced in standard technology engineering, our goal is to increase safety, reliability and the efficiency of the overall system.

Deployment of Small Scale Binary Power Plants

Besides the exploitation of high enthalpy geothermal fields, the development of low enthalpy resources is an important aspect to significantly increase the sustainable utilization of Indonesia's geothermal resources. With small scale geothermal binary power plants it is possible to use low enthalpy geothermal resources. Furthermore, binary power plants can be used as bottoming units for geothermal flash or dry steam power plants increasing the installed capacity.

Geothermal small scale energy provision in remote areas requires a holistic approach by addressing challenges in geothermal exploration, reservoir engineering, and power plant engineering. At many locations in Indonesia medium enthalpy / medium temperature resources can be found at depths of about several hundred meters, for example at 300-500 meters at Blok Langkoan, Lahendong geothermal field, North Sulawesi (Azimudin, 2001) or at about 600-800 meters at Atadei, East Nusa-Tenggara (Nanlohy, 2003), that could be utilized by means of flexible small scale binary power modules. Also power plant engineering and operation could be simplified significantly for such sites. Flexible plant sizes applicable at different geothermal sites can be realized based on modular setup and enable reliable operation and low maintenance. A prototype of such a versatile small scale binary unit has been developed. This 60 kW_e prototype binary power plant (Fig. 4) was presented at the WGC 2010 in Bali. Performance tests and improvement of the system are planned and will be conducted at the in situ geothermal laboratory Groß Schönebeck (Germany).

In addition to the development of binary power plants for remote areas, a demonstration binary power plant as a bottoming unit of an existing power plant is under preparation in collaboration with Indonesian partners at an existing facility. Parallel

Figure 4. Small scale power plant (60 kW_e) for geothermal power production in remote areas. Geothermal fluid inlet temperature: 145°C; Working fluid: n-Butane; Weight: 3 t, Dimensions (excl. cooling): 2.8x2.3x2.2 m.

to this activity several green field exploration campaigns are started to realize later the demonstration of the whole chain from exploration, reservoir development to supply of electrical energy. The next step will be to determine the geothermal potential in selected remote areas with small-scale communities, the knowledge of technology to access the potential reservoir, and the customer demand structure. This should be the base for a large-scale deployment of small-scale power plants, which need support of interested financing agencies and the Indonesian government.

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