Int. J. of Sustainable Water & Environmental Systems
Volume 8, No. 2 (2016) 77-85

Beyond Hydrothermal Energy: A Predictive Model Scopes Engineered Geothermal System and R&D Investment Opportunities for UAE

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Abstract

UAE can add EGS (Engineered Geothermal Energy System) to its initiative for Clean Energy and become self-sufficient in power generation and desalination. While EGS needs critical technology development in order to become commercially feasible, probably not until 2050, UAE's huge oil and gas drilling infrastructure and early lead in commercial hydrothermal energy provide a perfect opportunity to cost-effectively engage in Technology Development needed for EGS commercialization. The recent announcement (April 2015) by the US Department of Energy (US-DOE) of a five-year intensive EGS Demonstration Program is a watershed moment in the mainstream energy industry for Clean Energy Production. This is followed in July 2015 by an announcement from the Bill Gates Foundation of a $2 billion purse to promote innovative research and development needed for rapid deployment of various forms of clean energy as a vehicle for climate control and poverty alleviation. The emphasis on EGS was underscored in a feasibility study report prepared by an 18-member panel of specialists at the MIT Energy Initiative (2006), which unquestionably placed EGS as the long term Clean Energy option for commercial base-load electricity generation. The UAE apparently has more potential than the USA in EGS resources in terms of geological and socio-economic parameters; and more importantly, a much better investment opportunity and R&D infrastructure to take lead in developing and testing the critical technologies needed toward commercializing EGS: advanced drilling and well completion. Currently UAE's lead in geothermal energy is limited to conventional Hydrothermal Energy only. This article explores the much bigger opportunity waiting for UAE in unconventional, Hard-Dry-Rock (HDR) geothermal energy, known as Engineered (or Enhanced) Geothermal System, EGS. The ongoing hydrothermal power generation and desalination pilot project in UAE since 2013 will pave the way for starting EGS R&D, on top of existing massive oil and gas field infrastructure in the country. This article also sketches a road map akin to an EGS Energy Initiative. A two-component, first order approximate model is developed and presented. The model shows, with conservative estimates, that electricity from EGS can significantly meet domestic energy demand, and also add to energy export portfolio.

1. Introduction

UAE can add EGS (Engineered Geothermal Energy System) to its initiative for Clean Energy, and become a world leader as well. While EGS needs critical technology development in order to become commercially feasible, probably not until 2050, UAE's huge oil and gas drilling infrastructure and early lead in commercial Hydrothermal energy provides a perfect opportunity to cost-effectively engage in EGS Technology Development. Fig. 1 illustrates the incremental growth needed by leveraging the existing resource bases in order to achieve EGS world leadership in technology development. The ownership of a host of new technologies (intellectual property, know-how, allied services, etc.) in themselves in a world powered by EGS will ensure for UAE a strong economy, and at the least will provide base-load electric power for both domestic consumption and export.

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DOI: 10.5383/swes.8.02.008

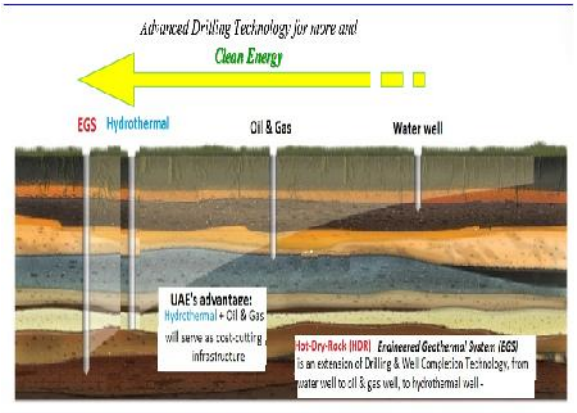

Fig. 1 New Opportunity for Abundant Clean Energy from Hot-Dry-Rock Engineered Geothermal System

Geothermal energy for commercial electricity generation has been growing in the world, and spurred by the quest for Clean Energy. UAE is now globally visible in this field, with Masdar City being one of the five cities in the world [1]. However, except in Perth, Australia, all geothermal plants are run by heat extracted from sedimentary basins characterized as low-enthalpy sources, and used on a limited scale for desalination, cooling, and low-temperature steam generation.

The purpose of this paper is to explore the potential for a thousand times larger geothermal source, called EGS, which stands for *Engineered* (or *Enhanced*) *Geothermal System*. The recent announcement (April 2015) by the US Department of Energy for a five-year long intensive EGS Demonstration Program is a watershed moment in the mainstream energy industry for Clean Energy Production [2]. In July 2015 the Bill Gates Foundation announced a $2 billion purse to promote innovative research for rapid development of Clean Energy [3]. The emphasis on EGS was underscored in a feasibility study report prepared by an 18-member panel of specialists at the MIT Energy Initiative (2006), which unquestionably placed EGS as the long term Clean Energy option for its feasible base-load electricity generation potential for centuries [4].

The US-DOE-sponsored study examined the potential of geothermal energy to meet the future energy needs of the United States. The panel concluded that geothermal energy could provide 100,000 MW or more in 50 years by endorsing for the yet-to-be-commercialized advanced technology known as EGS. Interestingly, the MIT findings reveal that UAE and many other countries have better potential for using the earth's deep heat sources (called Hot-Dry-Rock, HDR). Fig. 2 shows the concept of EGS, in which water in excess of 50 kg/s (~315 bbl/s or 18,867 bbl/minute or 27,169,811 bbl/day) is injected through a network of ultra-deep boreholes to reach hot, granitic rock at or above 250 ^{o}C. A network of induced fractures or other forms of conduits are supposed to act as a heat exchanger, and the superheated water returned to surface through other wellbores. Upon flashing, high-pressure steam is generated and used to drive steam turbines to produce electricity. The US-DOE program for EGS is focused on the huge challenges involved in this massive Heat Exchange System: prospecting for shallower and characterization of HDR, arguably the most challenging task of converting the HDR into an engineered heat exchange system. Appendix-A captures the essence of this imperative in the DOE-FORGE Program for EGS.

Currently EGS has not become a commercial entity due to lack of enabling technologies, and very high capital investment requirements.

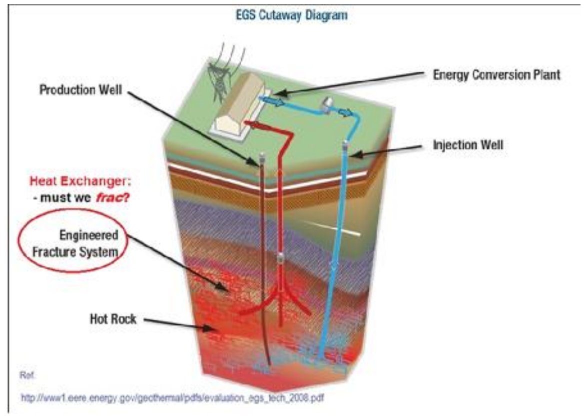

Fig. 2 Concept of EGS -- Steam- Turbine Electricity Generation using Engineered Heat-Exchanger. Made at Hot-Dry-Rock at Great Depth [5]

To achieve cost-competitive geothermal energy via EGS, significant advances are needed in, among other things, advanced drilling and completion technologies. UAE's huge oil and gas drilling infrastructure and fields will cut cost significantly for developing the necessary technologies. These technologies will also support ongoing development and expansion of the new Masdar City Hydrothermal Energy initiative.

The strategy should be to leverage and build from current geothermal technologies and resources to develop the advanced technologies required for EGS, while at the same time generating benefits in terms of domestic energy consumption and export capabilities in the near-, mid-, and long-term. This will require a systematic, sustained research and development effort by the UAE government in strong partnership with industry and academia to ensure full development of EGS.

Lastly, an *Innovative Technology Management* is suggested in the model of India's successful missile development program demonstrated by late APJ Abdul Kalam: harnessing the academic and R&D institutions into a robust and synergistic fast track research program. The Missile Man of India, with meager funding from the government of India, created a pool of 500+ scientific and engineering talents pulled from the six institutes of technologies and a couple R&D institutions [6, 7].

With over a dozen universities and private technology investor opportunities in UAE and the Masdar City, the government of UAE can forge a veritable technology initiative akin to a "mission mode" that India has demonstrated: achieving spectacular success in its Space Mission with indigenous technology development, and more importantly, at a fraction of cost that some other powerful countries had spent. Thus, UAE is poised to take lead in the development and ownership of the key technologies that the world, including the USA and other developed countries, are waiting for toward commercializing EGS.

This paper will draw attention to the most critical component of EGS, in which the new US-DOE EGS Initiative is believed to have taken sub-optimal approach: the method of creating the subterranean heat exchanger system by the World War II era technology: Hydraulic Fracturing. A better alternative could be Plasma Fracturing Technology (PFT) invented by this author [8], if rock fracturing must be adopted. A key barrier to EGS is induced earthquake, which occurs due to slippage of fracture blocks against each other due to lubrication by massive amount of injected water. The new Plasma Fracturing method does not involve injection of fluids for fracturing *per se*, and in conjunction with a network of closely-spaced and smaller

diameter wells can mitigate induced seismicity below threshold level.
Yet another much safer and immensely optimized heat exchanger design could be an adaptation of time-tested heating tubes for steam generation, for example, by mimicking the Babcock & Wilcox non-Explosive boiler design, which uses water filled tubes and de-nucleates boiling to generate steam more safely than either under-fire or fire-tube versions. This will also ensure generation of higher pressure steam and also better *energy to steam* conversion [18]. Toward this end, Microborehole Drilling System (MBS) merits serious attention. In 1994, Los Alamos National Laboratory (LANL) advanced a concept for drilling deep, small holes with diameters from 2-3/8-in. to 1-3/8-in., for exploration holes, for reservoir monitoring, and for production of shallow- and medium-depth low-productivity reservoirs. This concept for coiled-tubing-deployed micro drilling evolved from theoretical studies and lab tests, to field demonstrations of 1-3/4- and 2-3/8-in.-diameter boreholes [9].
Combining PFT and MBS can materialize in an efficient, cost-effective and safe method for EGS design.

2. Hydrothermal - a precursor to EGS in UAE

The area surrounding the Persian Gulf is particularly suitable for the development of geothermal energy due to its geographical location – it is where the Arabian tectonic plate meets the Eurasian plate; it contains the sedimentary basins of the Arabian Gulf; and the Western areas of Saudi Arabia and Yemen are also subject to volcanic activity – and geothermal activity is high. It is estimated [10] that the geothermal potential of the Middle East as a whole is around 230 GW (Fig. 3).
However, there is a caveat: the 230 GW potential accounts for hydrothermal component only, whereas the potential from Hot-Dry-Rock (HDR) energy could be more than 1,500 times. This can be appreciated with an apple to apple comparison between *Hydrothermal System* and *Engineered Geothermal System* potentials: while the former can just partially meet growing domestic energy need in the next century, the latter can fully meet energy consumption for centuries to come, and on top of it can generate huge export income. In addition to that, EGS technology ownership of UAE will open yet another veritable source of revenue.

The UAE has a substantial amount of geothermal energy hidden beneath its sandy surface – some estimate that there are tens of thousands of GW available – much more than was previously thought. It is noteworthy to underline another possible advantage for UAE in terms of HDR: the depth factor, because cost of EGS wells is overwhelmingly dominated by drilling and completion, which increases exponentially with depth. Given the tectonic setting of the Arab Peninsula, and also a long coastline and maritime areal jurisdiction, HDRs in UAE may be shallower.
This hidden power source, which is only recently being harnessed, has the potential to power a substantial share of the desalination needs in the region and makes this power source one of the most attractive renewable and economically-viable energy sources in the Middle East.
In terms of geothermal potential to produce electricity also power desalination plants [10, 11], experts in the field are looking to a pilot scheme which can generate 2,000m^3 of drinking water and produce up to 500 kW of electricity per day. Some experts predict that savings of up to 85% are possible (see Fig. 3).
Compared to solar powered desalination, a geothermal power plant has much lower footprint. This is important for UAE if generated electricity is to be considered for export earnings, too, because of limited open land area available.
To produce just 1m^3 of fresh, potable water per day requires anything between 50 – 200m^2 of solar panels, whereas one geothermal well-pad, which could also produce 20MW per day, would cover an area of around 100m^2, making it the renewable technology with the lowest surface land requirements per MW.
The competition can be understood and appreciated better by considering the land vs. population growth and far more domestic energy consumption projected over the next hundred years, as shown in Figs. 4 and 5. These projected data, however, also indicates that the ongoing UAE initiative for low-enthalpy *Hydrothermal* Energy will not suffice. Fortunately, another form of mining geothermal energy for electricity production has just emerged: the *Hot-Dry-Rock (HDR)* at far deeper depth than hydrothermal sources, which can generate thousand times more base-load electricity (See Table 1).

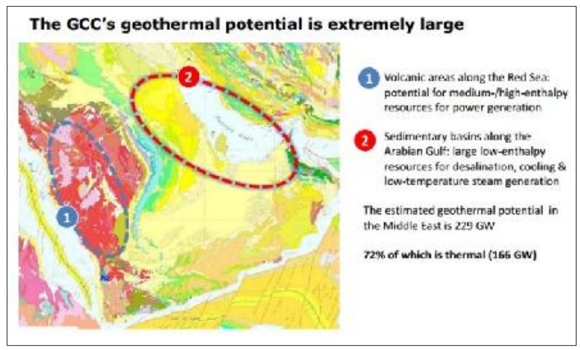

Fig. 3 UAE's Current Low-Enthalpy Hydrothermal Energy [10]

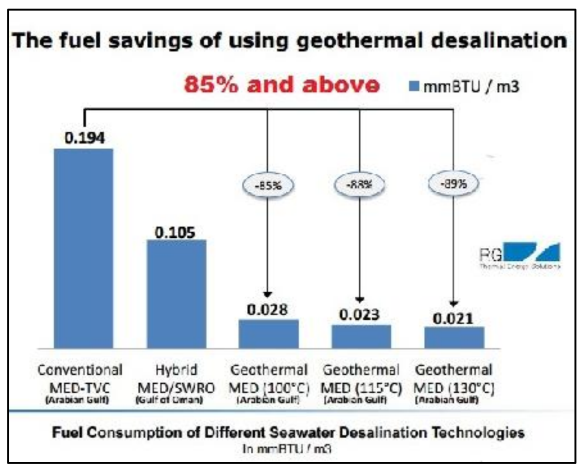

Fig. 4 Estimated Fossil Energy Savings for UAE from Implementation of Conventional, Low-Enthalpy Hydrothermal Energy Sources [10]

To understand the magnitude of the thermal energy or heat content of the rock at great depth in HDR-EGS system, it is useful to consider the following thought experiment [4]:

Imagine a 9 km long x 9 km wide x 1.0 km thick slice of rock below the ground surface, which is at an initial temperature of 250°C. Reasonable average values are 2,550 kg/m^3 and 1,000 J/kg °C, for the density (ρ) and heat capacity (C_p) of the rock, respectively. If this mass of rock is cooled through a temperature difference of 200°C to a final temperature of 50°C, then the heat removed is given by,

$$Q = \rho C_p V \Delta T = (2550\,kg/m^3)(1000\,J/{}^0C)(9.0km \times 9.0km \times 1.0km)(250\,{}^0C - 50\,{}^0C)$$
= 41.3 quad.

This is the energy, prorated at a conservative estimate of 1.63 quads at a recovery efficiency of only 4%, will fully meet the projected energy demand for UAE in the Year 2030, using only 81 km^2 HDR (approx. 0.1% of UAE's maximum HDR area of about 80,000 km^2).

Table 1. Conventional Hydrothermal Energy Resource is Miniscule Compared to Enhanced Geothermal (After [4])

Estimated U.S. geothermal resource base to 10 km depth by category.

Category of Resource	Thermal Energy, in Exajoules (1EJ = 10^{18}J)
Conduction-dominated EGS	(Quad = ExaJoule)
Sedimentary rock formations	100,000
Crystalline basement rock formations	13,300,000
Hydrothermal	2,400 – 9,600
Coproduced fluids	0.0944 – 0.4510

Therefore, an immediate task is to conduct a feasibility study for optimal site selection, using the new tool, *Global Bouguer and Free Air Gravity Anomaly Maps* [12], which has been recently made available (16 Apr 2015) at Masdar City based IRENA. The maps use ESA satellite gravity measurements to look for certain characteristics unique to geothermal reservoirs, including areas with thin crusts, subduction zones, and young magmatic activity. This helps determine which areas are most likely to possess geothermal potential, narrowing the search space. The publication of these maps is a first step towards developing a comprehensive geothermal prospecting technique. Future iterations could be produced at finer scales, integrating the satellite data locally with terrestrial data to further improve the quality of results.

3. A First Order Model to Assess the Impact of EGS for UAE Clean Energy Portfolio

In light of the possibility of a new, clean energy portfolio for UAE via geothermal, we construct a first order approximate model to forecast EGS capacity installation required to meet domestic energy demand as well as energy export from 2050 through 2150. The time window, and model parameters are selected based on the 2006 MIT Feasibility Report [4], which urges the USA government to facilitate massive R&D funding toward key technology development and testing to enable commercialization of EGS. The MIT report indicates that by 2050 EGS will attain technical maturity and economic parity with conventional base-load electricity generation methods (coal and hydrocarbon based).
The proposed model has two components:

1. UAE energy demand model, and
2. UAE EGS energy production model

The energy demand model is constructed by fitting a Power Law equation to UAE energy demand data taken from a published report [4]. These data are forecast between 2006 and 2020 (*blue* triangles in Fig. 5). First we fit a Power Law equation to these data, with excellent coefficient of correlation (R^2 = 0.97):

$$y = 9939.1x^{0.5108} \qquad (1)$$

with R^2 = 0.97
where, y = energy demand, MW; and x = number of years, starting at 1 for 2006, and ending at 15 for 2020 CE.

The *red* curve in Fig. 5 represents the fitted curve. This curve is then extended to 2150 (*blue* graph) using the above model. The predictive model can be fine-tuned once more historical data are available.

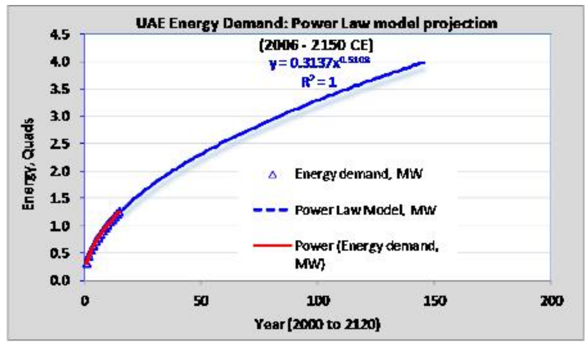

Fig. 5 UAE Energy Demand Projection up to Year 2120 CE. The Projection is based on a Power Law Model that Fits Estimated Energy Demand from 2006 through 2020

The **EGS energy production model** for UAE is constructed using the simplistic, analytical equation presented in the MIT Report [**4**].

$$Q = \rho C_p V \Delta T \qquad (2)$$

where,

Q = heat removed from the hot-dry-rock of the EGS
ρ = density of the hot-dry-rock (granite) = *2,550 kg/m³*
C_p = heat capacity of the hot-dry-rock = *1,000 J/kg °C*
V = volume of the hot-dry-rock, *m³*
T = temperature difference of *200°C* = initial temperature, *250 °C* - final temperature, *50 °C*

Fig. 6a shows UAE's potential for EGS energy (*blue* curve), which is calculated as a function of *land area equivalent* added with year for EGS energy production, as shown in Table 2. The model assumes a modest HDR capacity growth rate at 3%, expressed in terms of *land area equivalent.*
The purpose of Fig. 6a is to establish a first order approximate EGS capacity growth rate, which will be dictated by economics once the necessary EGS technology is available.
The energy demand curve is also superimposed in Fig. 6a (*brick-red* curve) in order to show the surplus EGS energy that will be available for export. By Year 2125, as seen in Fig. 6b, EGS energy in the form of grid electricity will fully meet UAE's energy demand, and thereafter a huge surplus electricity from EGS will be available for export.
The above estimate is conservative; it uses a modest 2.5% to 27.5% decadal growth in EGS energy extraction efficiency, spread over a century. This recovery rate is consistent with the 2% - 40% recovery efficiency envisaged in the MIT Report [4]. Much more energy can be made available for export if the EGS energy recovery rate is assumed greater than 4%.

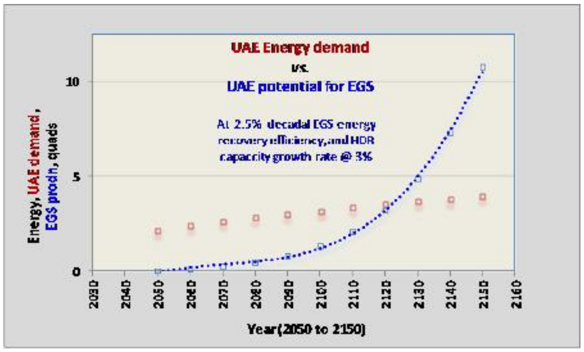

Fig. 6a UAE's Potential for EGS Energy Production

Table 2. Model based Conservative Estimate of UAE Energy Demand and EGS Electricity Potential

Year	Energy demand, quad	HDR area, km^2	Q, quad	Net Q, quad	Recovery eff.	EGS, % of demand
2050	2.19	4.00	2.04	**0.05**	2.5%	2%
2060	2.43	5.38	2.74	**0.14**	5.0%	6%
2070	2.65	7.22	3.68	**0.28**	7.5%	10%
2080	2.85	9.71	4.95	**0.50**	10.0%	17%
2090	3.03	13.05	6.65	**0.83**	12.5%	27%
2100	3.21	17.54	8.94	**1.34**	15.0%	42%
2110	3.38	23.57	12.02	**2.10**	17.5%	62%
2120	3.54	31.67	16.15	**3.23**	20.0%	91%
2130	3.69	42.56	21.71	**4.88**	22.5%	132%
2140	3.84	57.20	29.17	**7.29**	25.0%	190%
2150	3.99	76.87	39.21	**10.78**	27.5%	271%
UAE area, km^2		*80,000*	*HDR area capaciy growth rate/year*			*3%*

4. Enabling technologies for EGS commercialization: Advanced Drilling and Well Completion Engineering

The MIT Report [4] has identified a host of enabling technologies that will be necessary in order to commercialize EGS based electricity generation. The commercialization is predicated against base-load electricity generation at a price competitive with the conventional methods, such as coal and hydrocarbon fuel based thermal power generation.

The critical technology components sought are:

1. High temperature logging tools and sensors
2. Advanced drilling systems and Well stimulation technologies
3. Design and testing methodologies for developing large-scale, economically sustainable heat exchange systems;
4. Technical and environmental risk assessment and mitigation to facilitate EGS commercialization.

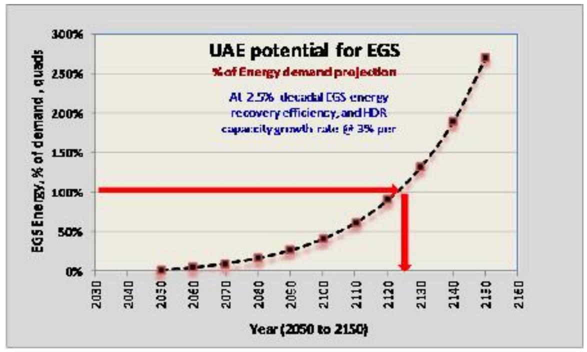

Fig. 6b Potential of EGS Electricity to UAE's Energy Demand and Export

4.1 Audit of Technology Status for EGS Commercialization

The purpose of the audit, as a SWOT Analysis, is to highlight the strength and weakness in UAE's existing energy infrastructure, and identify key opportunities and threats of competition.

Experience from the conventional geothermal and petroleum industries provides a solid foundation from which to make technology improvements. In the long-term, significant reduction in drilling costs will be necessary to access deeper resources, and the cost of conversion of the energy into electricity must be reduced. These improvements will rapidly move EGS technology forward as an economically viable means of tapping the nation's geothermal resources.

The 18-panel experts of MIT Energy Initiative assessed that EGS well construction activities resemble those employed in the oil and gas industry, but there are substantive differences. Geothermal wells are typically drilled at higher temperatures and harder rock (granitic), and with a much larger diameters in order to achieve high injection throughput (@50-80 kg/s, it amounts to 27,200,000 to 43,500,000bbl water per day. Oil wells these days are designed for rare maximum throughput of 10,000 to 30,000 bbl/day).

There are three critical assumptions about EGS technology that require thorough evaluation and testing before the economic viability of EGS can be confirmed:

1. Demonstration of commercial-scale reservoir – This requires stimulation and maintenance of a large volume of rock (equivalent to several cubic kilometers) in order to minimize temperature decline in the reservoir. Actual stimulated volumes have not been reliably quantified in previous work.
2. Sustained reservoir production – The MIT study concludes that 200°C fluid flowing at 80 kg/sec (equivalent to about 5 MW) is needed for economic viability. No EGS project to date has attained flow rates in excess of ~25 kg/sec.
3. Replication of EGS reservoir performance – EGS technology has not been proven to work at commercial scales over a range of sites with different geologic characteristics.

These assumptions can be tested with multiple EGS reservoir demonstrations using today's technologies.

4.2 Roadmap for UAE EGS Energy Initiative

Research and Development should be conducted in parallel with field projects to fill some long-term technology gaps. Some key EGS technologies are identified in Table 3. The following discussion pertains to the current status of technologies and requirements for further R&D [4].

Table 3. Opportunities for Key EGS Technology R&D in UAE

Engineering Task	Available Technology	New technology area	Importance for R&D in UAE
Borehole Drilling	Rotary drilling	Micro-borehole Drilling System Plasma Drilling System[1]	High High
Borehole Sensors Steering			Low Low
Borehole Casing			Low
Inter-well Heat Exchanger		Advanced Hydraulic Fracturing Plasma Fracturing System[2] Non-fracturing: MDS-based Heated-tube analog[3]	Moderate High High

[1, 3] Research in progress by the author.
[2] Invention by the author at Texas Tech University (2010).

The key technology requirements for immediate development stemming from this evaluation include [4]:

- PDC bits dominate drilling because of increased rate of penetration and longevity, but these bits have yet to be proven in geothermal environments. Roller cone bits are used in geothermal hard rock environments, a century-old technology that is robust but slow. Advancements in rock reduction technologies will probably be needed for EGS commercialization.
- High temperatures have hampered the introduction of oil and gas related technologies into geothermal well construction. The target operating temperatures of EGS wells (ε 200°C) are greater than those of almost all oil and gas wells. Steering tools can achieve adequate results from old technologies, but better steering and logging while drilling (LWD) tools are desirable.
- Logging tools for measuring temperature, pressure, flow, and other formation characteristics require heat shielding and can only be used for brief periods. While the drilling industry works within these limitations, more robust tools capable of operating in >200°C environments are needed. Monitoring tools emplaced in the wellbore for long-term operations measure many of the same parameters recorded during transient logging activity, but can also include other reservoir monitoring sensors such as those for monitoring induced seismicity. Advances in components, battery technology, materials, and fabrication methods are desirable.
- Economic viability will require design and construction of wells and well fields that efficiently exploit the geothermal resource. The design space for EGS well construction should include options for highly deviated directional wells, multilateral completions, multiple completion zones, and so forth.

These differences and the small size of the geothermal industry have retarded geothermal drilling technology relative to oil and gas technology. The geothermal industry has moved forward despite the disadvantages. For purposes of this evaluation, technologies associated with drilling and completing injection and production wells are taken to be the same as in the oil and gas industry.

5. Way Forward: Joint Industry-Academia Initiative for Low-risk-High-reward Projects

As we enter into a global race for clean energy production, it is prudent to take note of and be guided by APJ Abdul Kalam's *Innovative Technology Management* (ITM) formula (*see* Appendix B). Abdul Kalam proved to be a good project Team Leader, who successfully led the 78-strong team of scientists comprising India's intellectual wealth, and as an efficient techno-manager and a techno- expert delivered rare management competencies to raise a country's image in the international arena. Kalam ITM's three-point formula will go a long way to ensure UAE come ahead in the race:

- Develop a team spirit that nurtures exciting ideas, vitality, enthusiasm, curiosity and the desire to excel.
- For teams to be successful, the social and business environment must offer scope for innovation with risk-taking.

The AURAK--Research & Innovation Center can lead Joint Industry Program with multi-company sponsorship in all the areas of outside-the-box approach to long term energy production in the UAE and the Gulf to begin with. The following technology development projects merit consideration for participation in JIP:

1. Advanced Drilling Technology
2. Plasma Fracturing Technology
3. Microborehole Drilling System (MDS)

As already indicated, the thrust in the current DOE-FORGE Program is to extend the oil and gas industry technology base toward developing new drilling technology for injection of water and production. This author emphasizes on adding yet another role for advanced drilling technology: creation of a network of micro-boreholes connected to large diameter injection-production wells in order to replace hydraulic fracturing as a means of creating the gigantic subterranean heat-exchanger needed to realize EGS. Little over a decade ago this role of drilling was considered *vis a vis* hydraulic fracturing for efficiently developing one of the largest oil field in the world [13] At the same time, the author's proven concept of Plasma Fracturing with below threshold induced seismicity can remove a nagging environmental barrier to EGS commercialization [14].Since the invention of PFT in 2010, a low-energy variant of it has found limited application in North American oilfields [15, 16], and recently reported in Kuwait [17].

A host of Intellectual Properties (IP) is waiting in the wing, with low-risk yet high-reward opportunities by way of excellent return on investment in not so distant future via commercial licensing. Immediate possibilities are for local investments to create startup companies as spinoffs in AURAK's near-future Technology Park.

In particular, the Plasma Fracturing Technology (PFT) is ripe for investment as a startup, with continued R&D at AURAK for market leadership.

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Appendix-A

A. Hot-Dry-Rock: EGS —the Unconventional Geothermal System

The US Department of Energy (DOE) has launched this year (2015) a $29 million Feasibility & Demonstration program, titled FORGE —*Frontier Observatory for Research in Geothermal Energy* [2]. Techniques for extracting heat from low-permeability, hot-dry-rock (HDR) began at the Los Alamos National Laboratory in 1974. FORGE's mission is to enable cutting-edge research and drilling and technology testing, as well as to allow scientists to identify a replicable, commercial pathway to EGS.

For low-permeability hot-dry-rock (HDR) formations, the initial concept is quite straightforward, as depicted in Figs A.1 and 2:

- drill a well to sufficient depth to reach a useful temperature;
- create a large heat-transfer surface area by hydraulically fracturing the rock, and
- intercept those fractures with a second well.

By circulating water from one well to the other through the stimulated region, heat can be extracted from the rock.

This quantity of thermal energy, which could potentially be released from a 200 km^2 area of rock, is equivalent to the total amount of energy consumed annually in the United States, which has a total land area close to 10 million km^2. Estimated U.S. geothermal resource base to 10 km depth is 13,300,000 quads. At 2% conservative recovery, which translates to 2,800 years of energy consumption at 2013 level (Fig. A.2).

Fig. A.1 EGS is possible anywhere in the world, as long as the key components are implemented: drilling a network of boreholes interconnected by induced fractures, or other conduits to form a giant heat exchanger [4]

Therefore, the R&D activities of FORGE will focus on:

- innovative drilling techniques,
- granitic rock ("hot-dry-rock") stimulation techniques and well connectivity, and
- flow-testing efforts.

The seriousness of the US-DOE Project FORGE in order to develop enabling technologies toward commercializing EGS can be gauged from the fact that four of seven premier US National Laboratories have been engaged along with University of Utah in the FORGE Program:

- o Idaho National Laboratory - Idaho
- o Pacific Northwest National Laboratory - Oregon
- o Sandia National Laboratories - California
- o Sandia National Laboratories - Nevada

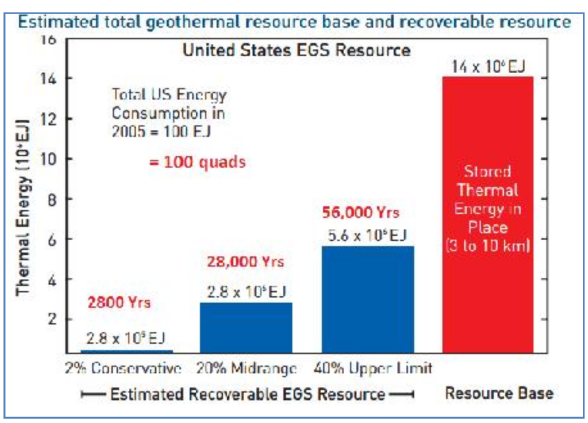

Fig. A.2 2013 US Total Energy Consumption: 97.4 quads [4]

Appendix-B

B.1 The Kalam Formula for Innovative Technology Management (ITM)

Dr Abdul Kalam, the iconic Missile man of India, has advocated the concept of *Innovative Technology Management* - a practical philosophy of management which should be learned and adopted by people working on challenging technology projects. Abdul Kalam has not only proved to be a good project leader who successfully led the 78-strong team of scientists comprising India's intellectual wealth, but is also an efficient techno-manager. It is rare to see a technocrat who delivers management competencies, an expert who has raised a country's image in the international arena. While working with scientists, Kalam developed team building and won the confidence of others to excel in performance.

His concept of *Innovative Technology Management*, wrote Kalam in his book 'Wings of Fire', is woven around an employee who is a technology person [6].

- The tree of ITM, if carefully tended, bears the fruits of an <u>adaptive infrastructure</u>:
  - o technology empowering institutions,
  - o the generation of technical skills among people, and finally,
  - o self-reliance and improvement in the quality.
- Recognize people for their *initiative* and *independence*, while acknowledging them for their *dependability* and *commitment*.
  - o "I value them for their *inter-dependence*, and champion *independent enterprise* while the rational manager serves co-operation."
  - o "I moot interdependent joint ventures, getting the force together, networking people, resources, time schedules, costs, and so on."
- It is essential to build a <u>dedicated team</u> with these behavioral competencies:
  - o Emphasize drive, innovation, and a participation competencies model.
  - o Let technology grow as a result of group activity based on the collective work of many individual talents.
  - o Adopt Maslow's model - the psychology of self-actualization at a conceptual level. The tree of technology management takes root only if there is self-actualization of needs, renewal, interdependence and natural flow.
  - o Infuse the characteristics growth patterns of the evolution process, which means that things move in a combination of slow change and sudden transformation.
  - o Maintain the natural law of latency in funding in order to foster a completely indigenous variety of technology management.
- Develop a Team Spirit that nurtures exciting ideas, vitality, enthusiasm, curiosity and the desire to excel.
- For teams to be successful, the social and business environment must offer scope for <u>innovation with risk-taking</u>.
  - o Kalam, too, confronted many challenges and failures during the course of his projects but always ensured for his teams an environment which allowed innovation and risk-taking.
  - o He advocated a novel idea of developing success criteria - a measurable parameter for each project. Out of the multiple and often conflicting sets of expectations for a team's performance, good teams are able to identify quickly the key persons with whom negotiations of the success criteria must take place.
  - o A crucial aspect of the team leader's role is to influence and negotiate with these key people for their requirements, and to ensure that the dialogue

continues on a regular basis as the situation develops.

- Kalam's wizardry of Technology Management is amply demonstrated by his astronomical successes as outlined below.

B.2 The Products of Kalam Innovative Technology Management (ITM)

An alumnus of the Madras Institute of Technology, Kalam worked for the Indian Space Research Organization (ISRO) where he helped launch India's first satellites into orbit. Later, Kalam worked on developing missiles and other strategic weapons; he was widely regarded as a national hero for leading India's nuclear weapons tests in 1998.

> *"One of the important lessons I learned in the space and missile program was not just how to handle success but how to deal with failure."* [7)

- Kalam joined the Defense Research and Development Organization (DRDO) in 1958.
- He moved to the Indian Space Research Organization (ISRO), where he was project director of India's first indigenous Satellite Launch Vehicle (SLV-III), which successfully injected the Rohini satellite in the near earth orbit in July 1980 and made India a member of the exclusive space club.
- He was responsible for the evolution of ISRO's launch vehicle program, particularly the PSLV configuration.
- Kalam took up the responsibility of developing indigenous weapons as the chief executive of the Integrated Guided Missile Development Program (IGMDP). He was responsible for the development and deployment of *Agni* and *Prithvi* missiles.
- From 1992 to 1997, Kalam was scientific advisor to the defense minister, and later served as principal scientific advisor (1999-2001) to the Government of India with the rank of cabinet minister.
- Kalam played a prominent role in the country's 1998 nuclear weapons tests, Pokhran-II, which made him a national hero.

The rocket and missile scientist was awarded the country's highest civilian honor - the *Bharat Ratna* - in 1997. In 2002, Kalam was named the country's President, and he held that position until 2007.