HYBRID GEOTHERMAL AND SOLAR THERMAL POWER PLANT CASE STUDY; GÜMÜŞKÖY GEPP

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ABSTRACT

Performance of air cooled ORC geothermal power systems are inversely related with ambient temperature, where summer temperature extremes can cause performance drops of up to 70% from design. Concentrating Solar Thermal power generation systems act inversely, almost in harmony, reaching peak efficiency during most of these ambient temperature extremes. The two thermal generation systems constitute suitable candidates for hybridization, as a way of "hedging production against ambient temperature fluctuations". BM Holdings is currently developing this concept in its Gümüşköy GEPP that is under construction, where the existing 6.6MWe geothermal power unit shall be complemented by a CSP system of adequate size in order to improve overall system efficiency while keeping a manageable Levelized Cost of Electricity (LCOE). A pilot solar field is planned to be erected in 2012 and full scale implementation is planned for 2013.

INTRODUCTION

The world's current levels of growing energy demands and global warming effects are forcing our global community to display an increasing effort in transitioning to renewable energy resources. On the other hand given the more expensive levelized cost of renewable electricity (LCOE), there is a strong demand for viable renewable energy projects.

Geothermal power is considered to be a sustainable renewable resource, because the heat extraction is negligibly small compared with the Earth's heat content and is constantly replenished by radioactive activity within the Earth. On the geothermal front, Turkey – being in a tectonically active zone – is the 7th in the world in geothermal potential, estimated at 2500 MWe and 31,500 MWt (Şimşek et. al, 2005). This potential is largely dormant, where according to Energy Market Regulations Authority (EMRA) 2012 data, the present installed geothermal power generation capacity in Turkey is 115 MWe, with 370 MWe more under development and construction (Serpen et. al, 2010; Mertoğlu et.al, 2010). On the other hand, this rate of growth is still slow, owing to a number of problems inherent in the technology and the share of geothermal in the total primary energy supply of Turkey is still below 1.5 % (Ediger & Akar, 2007).

Geothermal electric plants have until recently been built exclusively where high temperature geothermal resources were available near the surface. The development of binary cycle power plants and improvements in drilling and extraction technology helped extend geothermal power generation to lower temperature fields. However, thermal efficiency of geothermal electric plants is relatively low, around 10-23%. In accordance with the laws of thermodynamics, heat or energy (via pressure) extraction from lower temperatures still limits the efficiency of the process and increases LCOE from geothermal. Since there is no fuel cost, this does not necessarily affect operational costs. However it necessitates very high flow rates of geothermal brine to supply the required enthalpy, which leads to a high number of wells and pump costs. Plant CAPEX is therefore increased. In comparison, fossil fuel based thermal power plants can heat steam to much greater temperatures than geothermal power can and therefore reach higher efficiencies.

Another factor increasing LCOE is ambient temperature. Geothermal plants lose a lot of efficiency when operating in off-design high temperatures, owing to reduced pressure difference between the turbine input and output during hot summer days. As a result, geothermal power is still in need of subsidies in order to survive and spread.

HYBRID POWER PLANT CONCEPT

Approach

Once current renewable energy generation technologies are investigated, a very interesting match is observed between solar thermal and geothermal energy. Solar energy refers to energy that comes directly from the sun's radiation. It is utilized in two main ways, which are photovoltaic devices and through thermal heat collections. Photovoltaic devices absorb protons from the sun, which directly excite a flow of electrons to generate electricity. Solar heat can be used for concentrated into a heat transfer fluid, which operates a thermodynamic cycle to convert heat into electricity (Greenhut, 2010). The latter solar energy generation method is also referred to as Concentrating Solar Power, or CSP.

Both solar thermal (CSP) and geothermal energy generation methods operate a thermodynamic cycle, by heating a working fluid (or water) that drives steam turbines. Therefore, the two energy generation methodologies differ in heat collection but share the same power island structure.

Additional synergy is found in the inverse relation between the two technologies' operational efficiencies with ambient temperature. Air-cooled Rankine cycle geothermal power plants lose a lot of efficiency when operating in off-design high temperatures, such as during summer and daytime ambient temperature peaks. The base geothermal plant can produce only 60% of its peak generation in July (Greenhut, 2010). Solar thermal technologies operate at peak efficiency at exactly these times when ambient temperature is highest and efficiency of geothermal plants is at their lowest.

A proposition for a hybrid geothermal and solar thermal energy conversion system for locations having both resources can therefore be formulated based on these synergies between them. The hybrid system would aim to integrate an adequate capacity of CSP (without heat regulation) to a regular geothermal power plant, which would add sufficient enthalpy to the thermodynamic system to cover (i.e. eliminate) high ambient temperature related efficiency losses. Such a hybrid system would produce solar energy (equivalent to the value of added enthalpy), without additional power island investment, since this is already present in the geothermal system. The result would be a higher capacity renewable energy generation system with a more stable efficiency and good LCOE. Economic analyses already show that with respect to small size stand-alone ORC plants, much lower costs, up to 50% less, can be obtained with this technology (Astolfi et. al, 2011).

Availability of Resources at Target Location

Turkey has respectable solar radiation levels of up to 1980 kWh/m^2 in certain parts that can easily support solar thermal energy generation (Kaygusuz, 2011). More importantly, there are many parts of Turkey that have both strong solar radiation levels and geothermal resources (Figure 1).

The project location selected for this study is in Gümüşköy, Aydın, which was preferred for having both abundant geothermal resources suited to air-cooled ORC power generation as well as good levels of solar radiation (average 1311 kWh/m^2) and suitable land for placing solar fields.

The Gümüşköy geothermal field produces from a 2000 m deep reservoir of approximately 180°C, with a production temperature of 165°C. Gümüşköy Geothermal Power Plant (GK GEPP) Stages I and II are currently under construction, which will comprise 6.6MWe power units each for a total of 13.2MWe installed power capacity.

The current hybridization study was based on Stage I of the project that operates 6.6MWe power with 432 ton/hour of brine.

Preferred Hybridization Configuration

Hybridization studies commenced with systems combining geothermal energy generation systems with fossil fuel based thermal systems for superheating (Kohl and Speck, 2004). Other studies considered base-load oriented three way hybrids of CSP, geothermal and fossil fuel based thermal systems (cascading closed loop cycle) and geothermal and biogas hybrids (Kreuter and Kapp, 2008).

Geothermal and solar thermal hybrid power plants may be built with binary cycle (ORC) or flash steam geothermal plants on the geothermal end, and in different configurations. An example of solar–geothermal integration for electricity generation was proposed for the Cerro Prieto field in Mexico (Lentz & Almanza, 2006). Another example of solar-geothermal integration for electricity generation was built for Stillwater field in Nevada.

There are multiple ways that may be chosen to build geothermal and CSP power generation hybrids. Some of the power cycle configurations that have been investigated in the past are as follows (Greenhut, 2010):

1. **Working fluid superheat concept:** This approach utilizes solar heat to raise the temperature of the working fluid in a geothermal power generation cycle before it enters the turbines, resulting in higher working fluid exergy and power generation.
2. **Brine preheat concept:** This approach utilizes solar heat to raise the temperature of the geothermal brine before it enters the heat exchangers, resulting in higher brine enthalpy and thus higher power generation.
3. **Brine recirculation concept:** This approach utilizes solar heat to raise the temperature of a portion of the recirculating brine coming out of the heat exchangers to that of the fresh brine and add this recirculate brine into the feed to the heat exchangers. This results in a lower fresh brine requirement, thus higher power generation from the same field.
4. **Brine preheat/recirculation concept:** This approach utilizes solar heat to raise the temperature of both the geothermal brine before it enters the heat exchangers and also of a portion of the recirculating brine and feed this to the heat exchangers. This results in higher brine enthalpy as well as lower fresh brine requirement, thus higher power generation.
5. **Brine cascade reheat concept:** This approach utilizes solar heat to raise the temperature of the recirculating brine coming out of the heat exchanger to or above its

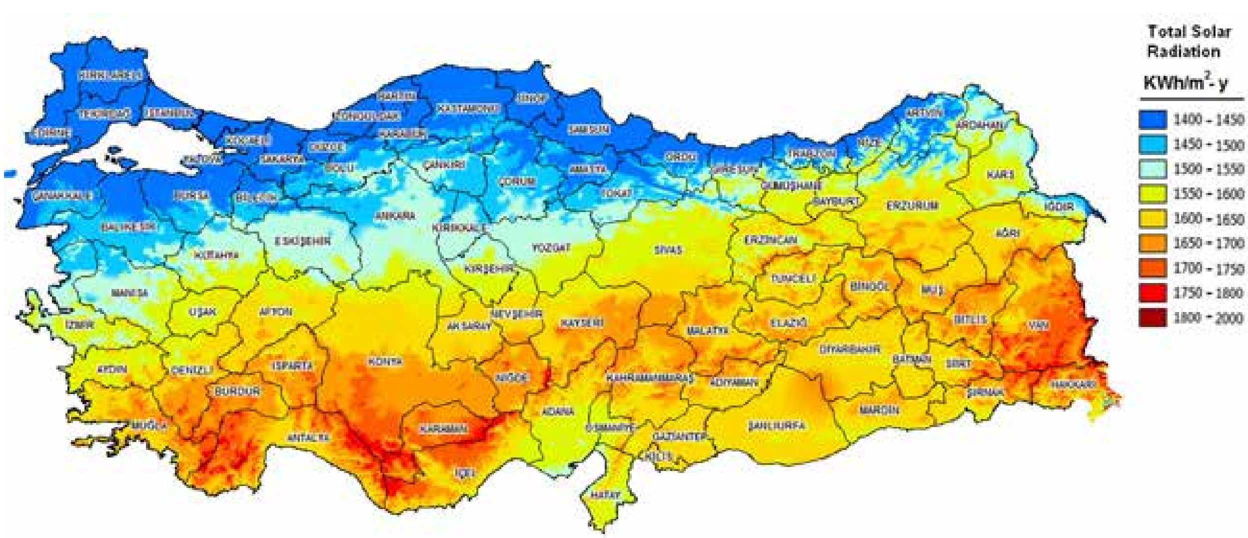

Figure 1. Solar radiation levels in Turkey (General Directorate of Electrical Power Survey Administration of Turkey)

original temperature and feed this to a second heat exchanger / power generation unit. This results in a much higher power generation from the same field.

Studies concluded that while the cascade reheat concept yields the highest solar utilization efficiency, the superheat and preheat systems produced the lowest incremental LCOE. A direct comparison between superheat and preheat systems suggests lower LCOE for the superheat concept, which eliminates thermodynamic losses in the heat exchangers.

Basis for Hybridization

The proposition for hybrid geothermal system and CSP in Gümüşköy GEPP are based on the following synergies that exist between them:

- **Availability of resources:** Geothermal reserves as well as strong solar radiation levels are available together in many locations in Turkey. One example is Gümüşköy in Aydın.
- **Maximizing operational efficiency:** Combining the two technologies enables CSP's operational peaks at high ambient temperatures compensate for the loss of efficiency in the geothermal system, thereby giving a combined overall efficiency that is higher than that of both systems.
- **Equipment sharing:** Both energy sources would share common equipment, such as turbines, condenser and heat exchangers. This allows joint use of the equipment for both solar thermal and geothermal generation.
- **Maximizing energy generation:** Using solar thermal energy to boost geothermal plant performance during the day, when solar radiation is at maximum, also helps realize the full energy generation of the installed power capacity. This enables higher renewable energy generation from the same geothermal field, which helps replace fossil fuel based generation.
- **Financial mitigation:** A hybrid system can mitigate the high cost of solar projects with the low cost of geothermal projects (Greenhut, 2010).
- **Ability to capture incentives:** Different economic incentives are available for different technologies. By combining geothermal and solar technology, hybrid systems can qualify for more forms of economic support (Greenhut, 2010).

CSP heat regulation systems have not been considered since in the classical sense, these are both extremely costly in comparison to the current considerations, as well as out of line with the synergy for maximizing operational efficiency. Partial regulation schemes through storage have not been addressed but may be assessed in a future study.

INDIVIDUAL SYSTEMS

Efficiency of ORC

When an air cooled condenser (ACC) is used as the plant's heat sink, then there exists a decline in net electricity generation of the turbines when ambient air temperature is high. At an extreme ambient temperature of 45˚C, this loss of efficiency can reach up to 80% (Figure 2). The reverse is also true, where a surplus occurs in energy efficiency during ambient temperatures below the optimum operating temperature.

The average brine temperature produced from the Gümüşköy Geothermal Field is 165°C, with 80°C return (re-injection) temperature. The plant design uses air-cooled condensers and therefore suffers a decrease in power generation during hot seasons owing to ambient temperature highs. Calculations show that the plant's power net production capacity drops from its maximum 7.3 MWe and design 6.6 MWe to as low as 3.9 MWe average for several months, depending on the ambient temperature (Figures 3 and 4). This corresponds to a total efficiency loss of up to 40%.

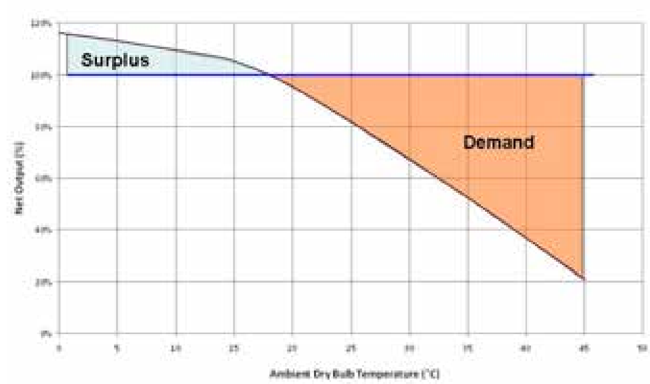

Figure 2. ACC ORC typical efficiency with respect to ambient dry bulb air temperature

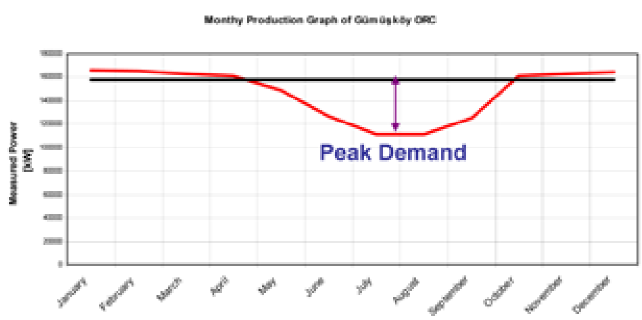

Figure 3. GK GEPP Stage I annual net power variation

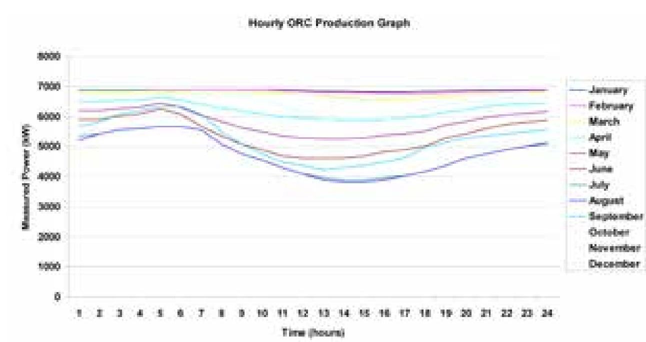

Figure 4. GK GEPP daily net power variation throughout the year

The initial objective is to build a solar field of adequate capacity in the adjacent land areas and utilize the enthalpy generated from the solar field to superheat the geothermal fluid to a temperature that would ensure 6.6 MWe (100%

design) or 7.3 MWe (peak generation) power generation through a much longer time period within the year. Naturally, the project economics must still consider shortcomings of the hybridization such as hot summer nights without solar radiation that would still lead to decreases in overall efficiency.

Efficiency of CSP

CSP systems are categorized as three different design alternatives: parabolic trough, power tower and dish/stirling which are basically solar thermal concentrating devices. Direct Normal Insolation (DNI) is reflected and concentrated onto a receiver or absorber where it is converted to heat, then the heat is used to produce steam to drive a traditional rankine power cycle. In Gümüşköy GEPP case study, parabolic trough collectors will be utilized. Parabolic trough system is line-focusing, and it uses the mirrored surface of a linear parabolic concentrator to focus direct solar radiation to an absorber pipe running along the focal line of the parabola. The heat transfer fluid (HTF) or water inside the absorber pipe is heated and pumped to the steam generator, which in turn is connected to a steam turbine to produce electricity.

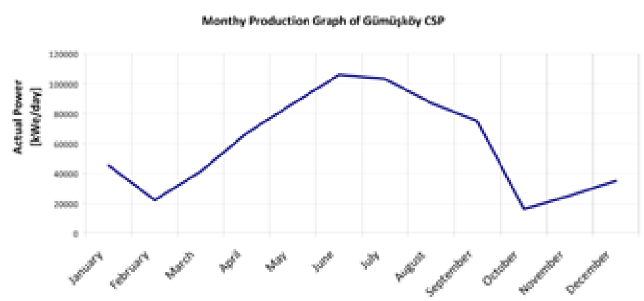

Figure 5. CSP daily net production capacity variation throughout the year

HYBRID PLANT DESIGN

The design was developed based on the working fluid superheat concept, by utilizing solar-derived heat to raise the temperature of the working fluid in the geothermal power generation cycle before it enters the turbines.

In the original GK GEPP design, the separators are located at individual well-heads. Geothermal brine is then transmitted to the power plant through separate transmission pipes in liquid and steam phases, also having two separate heat exchangers for each phase. A third heat exchanger was added to the binary loop in order to allow exchange of the solar-derived heat before transmitting the brine to the turbines. Superheated vaporized binary working fluid is then passed through the turbines, condensed through air cooled condensers and pumped back to the geothermal heat exchangers by circulation pumps (Figure 6).

Solar field capacity was selected based on the peak power deficiency (i.e. difference between design capacity and minimum production capacity) calculated from the Power Plant annual net production capacity variation (Figure 3) for the months of July and August. Next, the enthalpy amount corresponding to this production deficiency was calculated. Lastly, the amount of required CSP solar field was calculated in consideration of numerous manufacturers' specifications and the local solar radiation levels (Table 1).

A perusal of the annual net power variation graph shows that in certain times having cool (favorable) weather conditions as well as relatively strong solar radiation levels, the hybrid system produces above the power generation capacity of the power island (Figure 7). Some of the generated heat is therefore wasted during spring and autumn.

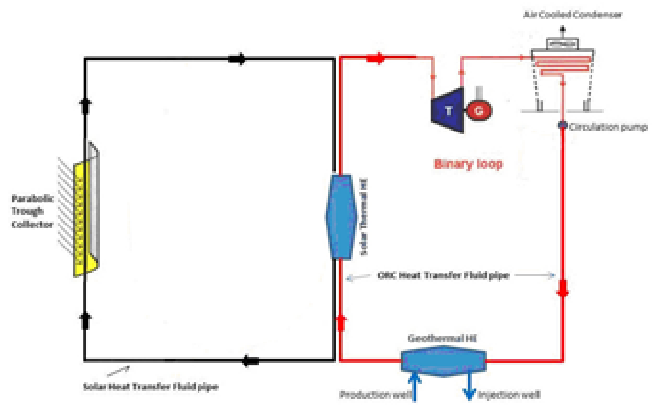

Figure 6. Gümüşköy Hybrid GEPP Proposed Cycle Diagram

Table 1. Solar Field Size Calculation Table

Design Item	Calculated Value for Hybridization
Average ambient temperature	28.67°C
Peak power deficiency	2,145.0 kW_e
Thermal power deficiency	19,500.0 kW_t
Thermal power def. incl. heat exchanger losses	22,941.2 kW_t
Design solar radiation	900 Wt/m^2
Solar field efficiency	63%
Total required solar field area	40,000. m^2

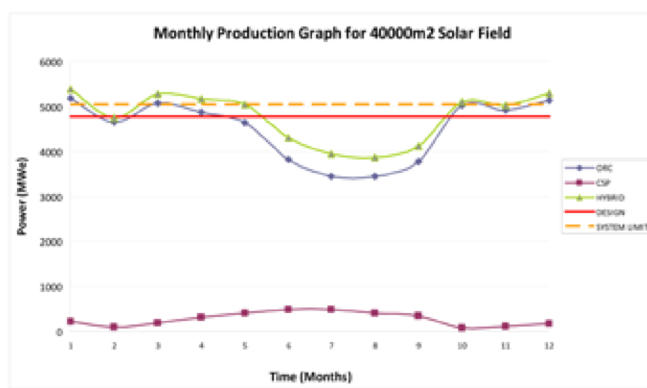

Figure 7. Annual net power variation for GEPP, CSP and HYBRID for Alternative 1 with 40,000 m^2 solar field area

Further trials were performed with reduced solar field levels in order to optimize the total LCOE, where solar field sizes of 50,000 m^2 (alternative 2) and 30,000 m^2 (alternative 3) were utilized (Figures 8 and 9).

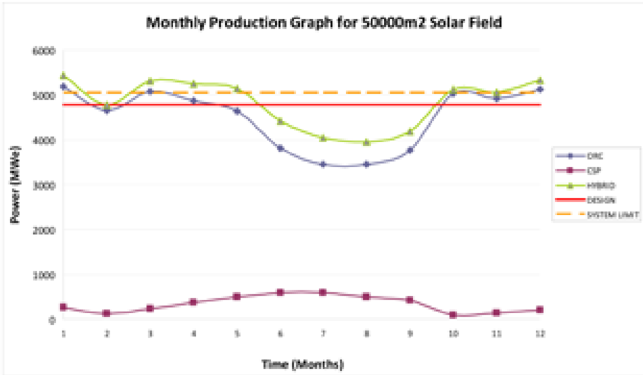

Figure 8. Annual net power variation for GEPP, CSP and HYBRID for alternative 2 with 50,000m² solar field area

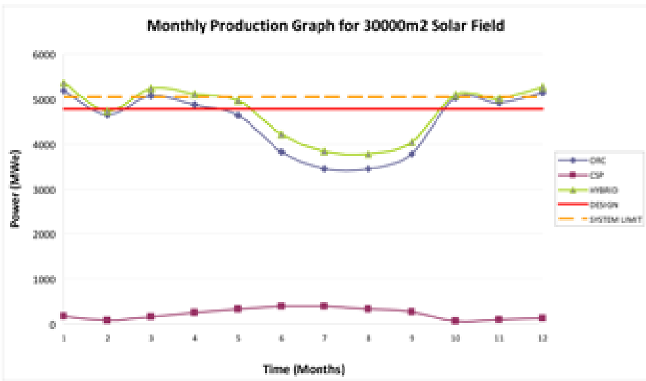

Figure 9. Annual net power variation for GEPP, CSP and HYBRID for alternative 3 with 30,000m² solar field

Operational data can be calculated as presented in Table 2 below.

Table 2. Project Performance

	Total Annual Production (kWh)[1]	Plant Efficiency
ORC	54,385,340.00	0.949
CSP (Alt.3)	2,631,959.00	0.267
Hybrid (Alt.1) 40000 m2	57,113,592.00	0.996
Hybrid (Alt.2) 50000 m2	57,245,800.00	0.999
Hybrid (Alt.3) 30000 m2	56,541,601.00	0.986
[1] Theoretical production above the system limit have been excluded in the annual power generation calculations.		

PROJECT ECONOMICS

Project economics have been calculated by determining CAPEX and OPEX values for 3 hybrid alternatives containing 3 different solar field sizes, coupled with the 6.6MWe Gümüşköy geothermal power plant.

Calculated values by utilizing price assumptions of 10.5 cents/kWh electricity, \$127/m² for solar thermal collectors (based on an indicative tender study comprising 3 vendors), and 7% annual interest rate as commonly applied for renewable energy projects are given in Table 3. The electricity rate is based on geothermal energy feed-in tariff rates currently implemented in Turkey. Solar thermal prices are higher at 13.3cent /kWh, however these were not considered for the solar generated part in order to stay on the conservative end of possible legislative limitations.

Table 3. Project Economics

	Cost of Plant (USD)	Annual power generation (kWh)	EBITDA (USD)	IRR (%)
ORC	20,000,000	42,299,286	4,441,424	17.37
CSP (Alt.3)	5,090,000	2,631,959	276,355	-
Hybrid (Alt.1) 40000m²	25,090,000	44,417,240	4,663,810	13.92
Hybrid (Alt.2) 50000m²	26,362,942	44,524,065	4,733,753	13.30
Hybrid (Alt.3) 30000m²	23,817,765	43,909,809	4,610,530	14.72

DISCUSSIONS & CONCLUSIONS

The above calculations show the most favorable returns from Alternative 3 (30,000 m² solar field area) with an IRR of approximately 14.72% for hybridization of the Gümüşköy GEPP project. On the other hand as this is an early study, further work is required on the following:

- An unregulated CSP applications would take 2-3 hours for the working fluid to reach the superheating temperature (150°C or above), which would lose valuable time from the high solar radiation time zone. A better solution would be to utilize a portion the geothermal system's still high production efficiency during cool morning times and for rapidly heating the CSP working fluid to operating temperature. This can be accomplished by allowing the system to run in reverse (having the CSP heat exchanger cool the geothermal system) for a short period each morning. The net effects of this configuration have to be analyzed in the succeeding study.
- It was noted total enthalpy produced by the hybrid system exceeds the peak power generation capacity of the power island during some spring and autumn days and an optimization was performed with reduced solar field sizes. However, these calculations were carried out only as rough approximations based on daily average temperatures and not hourly temperatures. Figure 10 shows the significant waste and certain gaps formed by hourly variations, which means a more detailed optimization that will calculate total annual energy generation in consideration of all hours of the year is required for investment-grade accuracy.
- An analytical modeling tool (for estimating efficiency, energy generation and financials including benefit/cost, LCOE for different fields and resources) is seen as the next helpful step for better optimizing for system configuration, equipment selection and size selection functions. This tool would also serve as the stepping stone for adapting the hybridization scheme to other low to medium enthalpy geothermal fields.

A lot of exploration work goes to waste owing to below ideal temperatures discovered in the reservoirs. By superheating these geothermal fluids via CSP, energy generation from these resources can also be made viable. This would potentially increase any geothermal countries' energy generation potential and jump start a high number of new power projects as well as risky exploration initiatives. In both cases of energy generation, the projects' economic viabilities increase and the projects become attractive for private funding.

Meanwhile for Gümüşköy GEPP,

- A detailed model shall be constructed in accordance with the above considerations, which yielding a positive IRR value;
- A pilot CSP field shall be coupled with the existing 6.6MWe geothermal system and run for a period of 6-12 months for observing actual production values and contribution to the overall system,
- A complete system design shall be developed and 70-80% of the design solar field size shall be integrated as Stage I, in order to compensate for any over engineering errors,
- Solar field shall be increased to full calculated size and extended to include hybridization of the second 6.6MWe unit.

Future studies may include system optimization of hybrid systems including working fluid selection, heat exchanger modifications, improved materials etc. and further optimization studies by introducing partial regulation via heat storage in order to spread excess enthalpy over to continuing deficiency zones.

EDITOR'S NOTE

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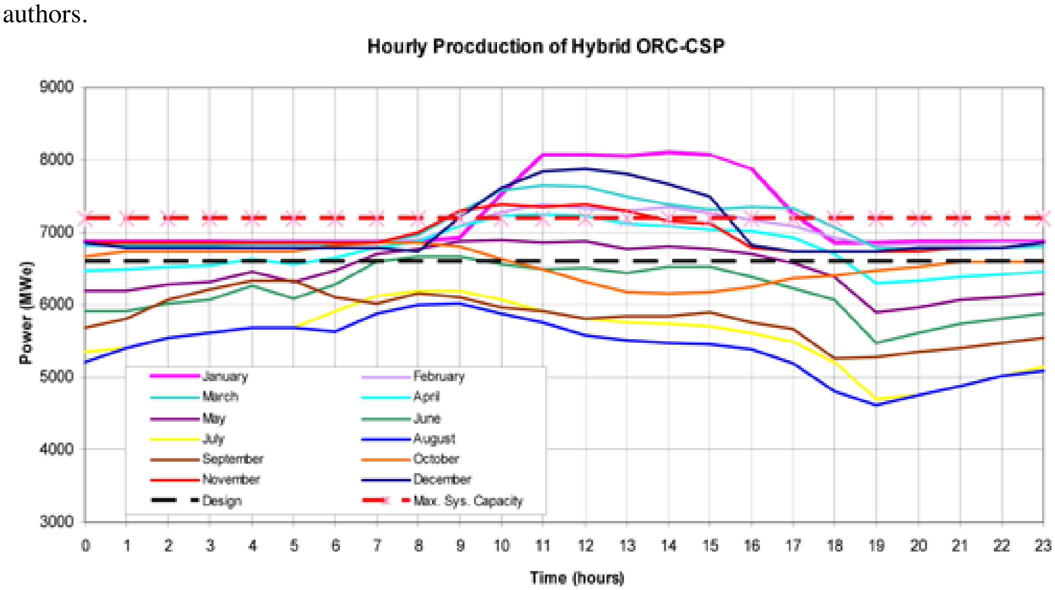

Figure 10. Hourly net power variation for the hybrid system vs. max. system capacity (upper dashed line)