A Post-Audit of Geothermal Development in California's Imperial Valley

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Received September 5, 2014; Accepted September 8, 2014

Abstract: This paper presents a post-audit of a 1978 examination of economic impacts of geothermal energy development in the Imperial Valley Region of California. It is intended to demonstrate the usefulness of this approach in evaluating the validity of renewable resource development in general. The 1978 examination based its estimates on a projection of 4500 MW of electricity generation capacity developing in the Region by 2020, and identified other applications for the geothermal resources as well (e.g., direct use as a heat source). It also projected significant economic gains and a minimum of negative side-effects. Today, the geothermal electricity generating capacity is less than a quarter of what was projected. While projects currently in development could more than double this capacity by 2020, installed geothermal capacity in Imperial Valley would still fall far short of the 4500 MW originally predicted. We examine several possible reasons for the shortfall. These include economic viability issues of geothermal resources, technical problems with geothermal resources, cost to generate electricity from geothermal sources compared to price received for it, lack of adequate long-distance electricity transmission line capacity, and concern over negative side-effects. We find that estimates of the amount of electricity generation capacity that can be supported by geothermal fields in Imperial Valley have been significantly revised downwards. Further, recent electricity wholesale data suggest prices are often lower than the levelized cost of generation from geothermal. Constraints on the ability to export electricity out of Imperial Valley also appear to have been a factor limiting development.

Keywords: Geothermal energy, development post-audit, resource characterization, extraction issues, electricity generation, transmission, economic impacts, Imperial Valley

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DOI: 10.7569/JSEE.2014.629512

1 Introduction

In the mid-1970s a multidisciplinary study was undertaken assessing the development potential of geothermal energy in the Imperial County of California[1]. The geothermal resource base there was identified as among the largest accessible in the US, but the Region had only hosted two small pilot plants by then. At issue at the time of the study was whether greater geothermal development was economically viable and could be undertaken with net positive socioeconomic and environmental impacts for the County's residents. Imperial Valley is a prime agricultural area of the country with a small population, limited infrastructure, and unique ecosystems. Saline contamination from geothermal well blowouts or pipeline breakages could render affected land unfit for cultivation for decades, and tilting of the tiled irrigation canals from land subsidence or damage from induced seismicity associated with the extraction and injection of geothermal fluids could result in very expensive repair costs.

Rose et al. [2] based economic projections on 4500 MW of installed geothermal electricity generating capacity in the Imperial Valley by 2020. This study also identified additional uses of the resource for industrial purposes, such as canning and refrigeration. The analysis indicated a minimal likelihood of negative environmental side-effects, minimal strain on infrastructure, and minimal socioeconomic disruption. At present there is about 700 MW of installed electricity generating capacity in the Imperial Valley (Figure 1). Plans exist to build more than 830 additional MW of geothermal generation by 2020 [3], but even this would still leave the Imperial Valley with far less geothermal being produced than was predicted in 1978. Moreover, there have been very limited industrial applications. On a positive note, there have been very minimal negative side-effects with the geothermal development that has occurred.

This paper analyzes some of the reasons for the shortfall in installed electricity generation capacity. It focuses on conditions related to factors assessed in the original study, as well as additional factors identified more recently. We conclude that the main causes of the shortfall are low prices offered for electricity generated, downward revisions of the amount of electricity it is possible to generate from geothermal in Imperial Valley, and lack of transmission line capacity to export electricity to other regions that have a demand for it.

The study also serves as an example of a post-audit that could be applied to other energy development scenarios, both renewable and non-renewable. Such post-audits are rare on most topic areas, but especially important for renewable

1 The study was performed by researchers from the California Institute of Technology (Caltech) and the University of California, Riverside (UCR). It was funded by the National Science Foundation (NSF) as one of the first Research Applied to National Needs (RANN) grants. The study also dovetailed with the US Energy Research and Development Administration (the precursor to the US Department of Energy) selection of the Imperial Valley as a demonstration site. Details of the NSF study can be found in Rose & Edmunds [1].

DOI: 10.7569/JSEE.2014.629512

energy development. With limited actual operating experience, we are dependent on projections on which to base private investment and public policy decisions. Proponents and opponents of renewable energy development sometimes make exaggerated claims that widen the range of uncertainty. All stakeholders would be well served by more information, validation techniques such as the one presented in this paper, more accurate projections, and more timely audits that may lead to mid-course corrections. This paper provides an opportunity to examine ways in which impact analysis may be improved by determining causal discrepancies between predictions and actual development.

2 Geothermal resources

Electricity can be generated from geothermal fields by making use of the heat resource underground, via fluid contained in permeable rocks, to create steam to rotate turbines. After the heat is extracted, much of the cooler fluid is injected back into the geothermal reservoir to maintain reservoir pressure and also to dispose of potentially hazardous substances in the fluid [4]. Geothermal resources are renewable if this extraction/reinjection cycle is managed in a steady state manner, though this is typically at a relatively low level. Unlike most other renewable technologies, geothermal has the advantage that it is suitable for providing reliable base-load power regardless of weather conditions.

Some geothermal fields can be used for electricity generation with the application of established technologies more than other potential fields (for example, low permeability resources may benefit from Enhanced Geothermal System [EGS] technology). The major categories of geothermal technologies are: Dry Steam power plants, which can be used to generate electricity at fields that produce mainly vapor (vapor-dominated fields); Flash Steam power plants, which are used at geothermal fields containing a mixture of pressurized liquid and vapor (wet fields); and Binary Cycle power plants, which are used at wet fields in cases when the liquid is highly corrosive, expected to cause scaling, and/or the geothermal resource is of a relatively low temperature [5]. Though more than 90% of geothermal fields exploited on an industrial scale for electricity generation are wet fields, about half of the geothermal energy generated in the world comes from six vapor-dominated fields [4]. In the USA, the only installed Dry Steam plants are at the Geysers in California [6]. In principle, all that is required for a Dry Steam geothermal plant to function is for geothermal steam to be piped from production wells to a steam turbine [5]. In practice, mechanisms for removing particulate matter, condensate, and potential air pollutants are often required, but the overall resulting system is still relatively simple. Dry Steam power plant technology is the oldest method of generating electricity from geothermal resources; in 1904, steam from the Larderello geothermal field in Italy was used directly to drive an electric dynamo and generate electricity from a geothermal field for the first time [7].

The Imperial Valley possesses wet steam fields that produce a mixture of liquid and vapor, and cannot use Dry Steam plants; most operations in the Imperial

DOI: 10.7569/JSEE.2014.629512

Valley use Flash Steam generation technology for electricity production [8]. In wet fields the vapor must be separated from the liquid to prevent damage to power generation equipment; the simplest technique for this involves centrifugal separation. Once separated, the vapor can be used to rotate a steam turbine [5]. Wet fields yield varying proportions of vapor and liquid, and sometimes contain high concentrations of chemical components (mainly chlorides, bicarbonates, sulfates, borates, fluorides and silica), which can cause scaling in equipment and add to maintenance costs. The water portion is disposed by reinjection, due to its high chemical content [4] and to provide pressure support to the geothermal reservoir. There has also been some use of Binary Plant technology in the Imperial Valley (Table 1). In a basic Binary Plant, the geothermal fluid provides heat to a second "working fluid", with the working fluid being the substance that passes through the turbine and other electricity generation equipment. Working fluids with a low temperature of vaporization can be selected, providing vapor to rotate a turbine even when utilizing low-temperature geothermal resources [9]. Like Flash Plants, the fluid is disposed through reinjection after the heat has been extracted [5].

2.1 *Development of the Imperial Valley geothermal resource*

Imperial Valley contains many Known Geothermal Resource Areas (KGRAs), though estimates of the electricity generation potential of these resources have varied over the years with the discovery of new geothermal fields within the Valley, changes in economic appeal of geothermal compared to other generation technologies, and increased knowledge of geothermal field characteristics [12]. The Brawley field in particular was downgraded as land access, geochemistry, and stability issues became known after 1981; though technological solutions may exist, these are not always economically feasible. There is also a possibility that the East Mesa field was managed poorly and thus depleted faster than would be optimal, further reducing resource estimates. Salton Sea, however, is still considered to have high potential [13].

The 4500 MW of geothermal energy development that Rose et al. [2] estimated to be possible in Imperial Valley is thus higher than the potential considered to exist today. A more recent estimate considers there to be closer to 2500 MW of geothermal potential in Imperial Valley (Table 1). However, other studies and workshops have projected that there is a greater potential to develop geothermal generation than is suggested by the Table 1 estimate [14, 15]. The generation potential of a geothermal well is dependent on both the temperature and the expected flow rate of the geothermal fluid; however, the quality of the well for power production can also vary with factors such as dissolved solids content. As of 2009, approximately 700 MW of geothermal plant nameplate capacity had been installed in Imperial Valley, although measured capacity of these plants is only 600 MW due to issues preventing full realization of technical potential of some plants (Figure 1).

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Table 1 Geothermal Resource Estimates for Imperial Valley [10, 11].

Name of KGRA	Resource Estimates (including existing development) (MW)	Resource Depth (feet)	Resource Temperature (°F)	Total Dissolved Solids (TDS) (ppm)	Plant Technology Employed
Salton Sea	1,750	3,000-10,000	510-650	250,000	Flash
North Brawley	135	480-560	480-5600	50,000-250,000	Binary
South Brawley	62	11,000-14,000	470-530	250,000	no plant
East Brawley	129	10,000-14,000	410-560	54,000-160,000	no plant
Heber	142	2,000-10,000	300-330	14,000	Flash & Binary
East Mesa	148	6,000-10,000	300-350	1,600-26,000	Flash & Binary
Niland	76	9,000-13,000	500-550	250,000	no plant
Glamis	6	5,000-11,000	250-400	no data	no plant
Dunes	11	4,000-10,000	250-400	4,000	no plant
Superstition Mountain	10	1,500-7,000	225-440	no data	no plant
Total	2,469				

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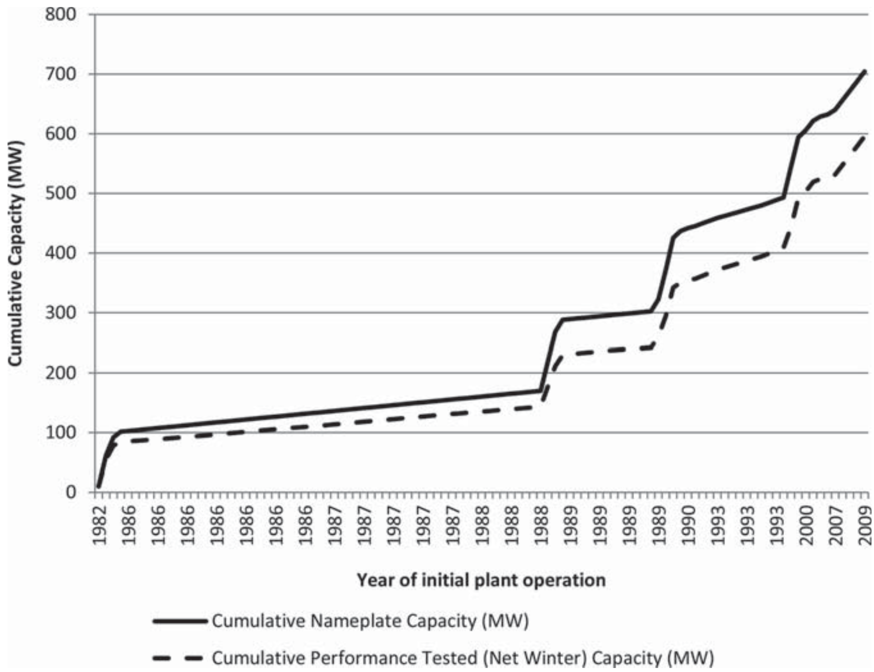

Figure 1 Cumulative installed capacity of geothermal plants in Imperial Valley over time, comparing nameplate capacity to tested performance [16].

The geothermal resource in Imperial Valley has not proved as easily extractable as many investors might have hoped, and not all geothermal plants installed there have been able to operate at "nameplate" (maximum designed output) capacity (Figure 1). ORMAT Technologies Inc., which owns and operates the North Brawley Geothermal Power Plant in Imperial County, was by 2013 only able to operate the plant at 27 MW instead of the expected 50 MW, and this only after significant additional capital expenditures [17]. Additional equipment for electrical generation was required because of high volumes of undissolved solids extracted at this particular site with the geothermal fluids, which cannot be removed cheaply [18]. Complications such as this can discourage investors and can also result in less geothermal generation being brought online than was predicted by original assessments.

3 Historical Projections

3.1 Background

Geothermal energy, like other renewable energy sources, is desirable to countries and regions for a combination of reasons including its ability to reduce

DOI: 10.7569/JSEE.2014.629512

local contributions to global climate change, to reduce ordinary air pollution emissions, and to make use of indigenous resources that lower the need for dependence on imports. Geothermal energy in many regions is economically viable in the absence of subsidies or policies intended to increase shares of low-emission energy supply. Rose et al. [2] examined the case of geothermal development in California's Imperial Valley and projected that utilization of the area's geothermal resources could bring significant economic benefits to the region. However today, despite the predicted economic benefits and also despite the State of California being comparatively active in support of low-emission generation technologies, the installed geothermal capacity in Imperial Valley is only a small fraction of the amount that analysts initially considered feasible and viable.

Every new business activity takes place in a host community and, whether small or large, requires some form of approval, such as zoning authorizations, building permits, and inclusion in a general plan. A large-scale geothermal development initiative would be highly visible and would bear strong scrutiny at all levels. At the highest level of decision-making within the County, there would be acknowledgment of its potential to stimulate the regional economy but also concern about unintended side-effects relating to environmental and societal concerns. Hence, development plans are usually accompanied by formal environmental impact statements and less formal economic impact reports. The Rose et al. [2] and Rose and Edmunds [1] studies contributed to the latter.

Energy development plans are often part of a larger national context. Geothermal energy became more attractive after the US energy crisis began in 1974. The major national policy strategy was to pursue energy independence through a combination of conservation, technological innovation and increased extraction of indigenous resources. Many of these resources are in areas of the Western US, characterized by pristine environments and low populations with a limited local demand for the products of the energy resources. De facto, these areas were being asked to contribute to a national goal, even if there was a limited need for the resource itself and potential for significant negative spillovers. Thus, acceptance of development in the host region became a key link in the three-part chain whose first two links are national policy and private profitability [19].

Renewed interest in geothermal development has begun in California due to a broader policy concern, in this case climate change. The California Global Warming Solutions act, Assembly Bill (AB) 32, requires that the state achieve a target of 33% of its electricity demand being produced by a mix of renewable resources by the year 2020. The Renewable Portfolio Standard (RPS) provision of AB 32 does not specify the target for any single renewable, but geothermal electricity is already playing a significant role in the mix statewide, especially since some other renewables are not turning out to be as economically attractive as previously projected in absolute terms, as well as in relative terms of competition from relatively inexpensive natural gas [20].

DOI: 10.7569/JSEE.2014.629512

3.2 *Initial Projections*

Increased geothermal development in Imperial Valley was expected to reduce unemployment and diversify areas of employment, among other benefits [2, 21]. Estimates of the amount of geothermal development expected in the area by 2020 varied; Rose et al. [2] used an estimate of 4500 MW installed capacity by 2020 to predict effects on the Region, while Pick et al. [21] expected development of between 1250 and 8500 MW. Pick et al. [21] also expected geothermal to be added in increments of between 100 and 150 MW per year.

Some of the broader issues surrounding geothermal energy development identified in a NSF study in Rose and Edmunds [1] are the regional aggregate and distributional economic impacts. Geothermal energy extraction and conversion are highly concentrated and capital-intensive activities. This means that the direct jobs are likely to be relatively meager in number, rents will flow to a few land/royalty owners, and profits will flow out of the region to primarily non-resident investors [22]. This mutes the beneficial economic impacts, which can be large if multiplier effects are large and widespread, but this is not likely the case in a region that imports so much of its demand for goods and services, and has only a few prominent sectors of its own. The direct and indirect impacts can also be enhanced if the geothermal resources are able to attract labor-intensive industries, and ones with linkages up and down the supply chain to other sectors of the regional economy.

But by 2009, Imperial Valley only had 704 MW of installed nameplate capacity, and, except for 1988 and 1989, has not installed anywhere near the 100 MW each year projected [16]. Reasons for the lack of development despite apparent economic benefits could stem from low electricity prices leading to unprofitable investment opportunities, technical problems in extraction or conversion to electricity raising the costs of generating electricity, greater environmental concerns arising than predicted by original studies, difficulties not considered such as transmission line capacity constraints or public policy and planning obstacles, or some combination of the aforementioned factors.

4 Potential limitations to Imperial Valley's geothermal development

4.1 *Technological challenges*

For a successful geothermal project the following three resource elements have to be present: (1) favorable temperature gradient; (2) availability of water for injection and subsequently producing steam; and (3) presence of natural fracture networks, coherent and permeable sedimentary formations, or appropriate completion techniques in unconsolidated formations. Dissolved solids in geothermal fluid can precipitate onto the walls of the natural fractures [23] through which the fluid is extracted for use in electricity generation; if this occurs, then the volume of fluid able to be extracted from the geothermal field will gradually reduce and thus the generation capacity of the plant will reduce also. The geologic structure

DOI: 10.7569/JSEE.2014.629512

of the flat-lying Imperial Valley is alluvium over marine deposits (composed of layers containing clay and large amounts of silt and unconsolidated sand [often 20-40%]), with several faults including the San Andreas fault running through the area. Bedrock in this sedimentary basin is typically at a depth of 6700 m. Most of the producing sections in all the fields are characterized by low porosity and high resistivity [24]. Geothermal fields in the Imperial Valley have been challenging to produce from due to the high dissolved solid content (Table 1) causing scaling in pumping and filtration equipment, and also creating buildup in production and reinjection wells [25]. Although technology exists to address some of these issues, it can require high capital expenditure and hamper development, as has happened recently at the North Brawley plant [26]. The understanding is the scaling issue has been resolved in Salton Sea and Hudson Ranch [13, 27].

The major categories of technologies used to improve utilization of geothermal resources include improved seismic imaging and interferometry [28, 29], characterizing high permeability distribution, monitoring the steam/fluid front, and stimulating the fracture network (although less relevant to the Imperial Valley geothermal fields). Figure 2 shows different types of geothermal resources with their associated risk and reward profile. The most common one is the low temperature and coproduced geothermal resource where the untapped resource is estimated at 120 GW in the US. Given the size of this resource and its relative abundance, it is considered as a low risk, low reward type. The characteristics of the other intermediate resource types that can benefit from innovative exploration technologies and those associated with the permeable sedimentary resources are shown in Figure 2. The one with the highest potential for growth is the EGS, with

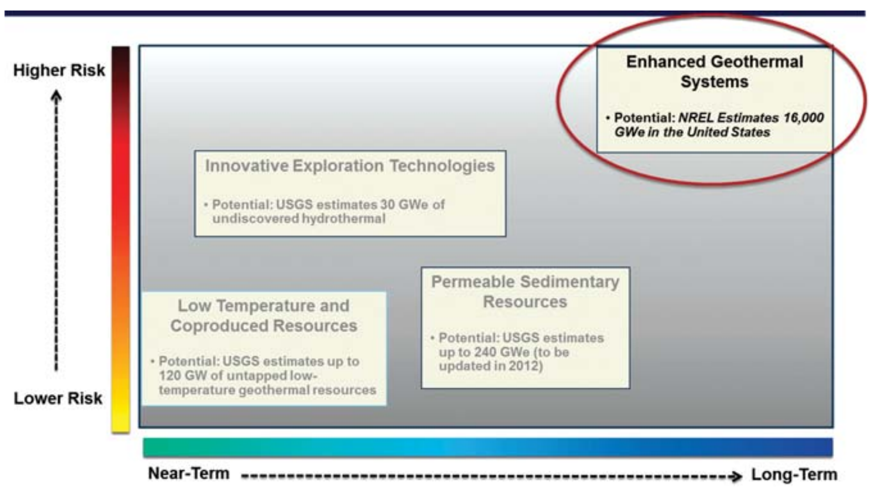

Figure 2 Types of Geothermal Resources and their Risk/Reward Profile (Natawani [30] and the DOE website).

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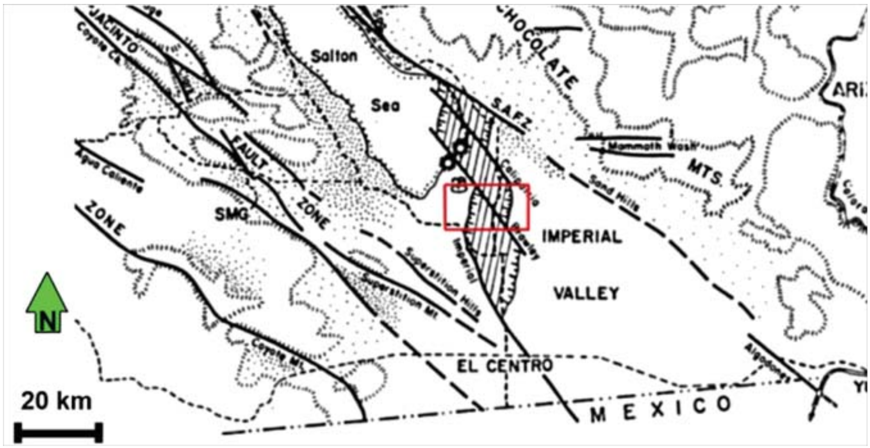

Figure 3 Fault map showing the Salton Trough, as well as the Brawley Field study area, see text. The patterned lines show the spreading centers. Abbreviations: SMG, Split Mountain Gorge; S.A.F.Z., San Andreas Fault Zone [31].

potential resource size of 16 000 GW. We elaborate on the EGS with more details on its risk/reward profile in section 5.

The Brawley field in Imperial Valley is a highly faulted shallow reservoir within relatively young, unconsolidated sediments. Figure 3 shows the field map with the associate faulting [31]. Extensive work to better characterize the fracture network was carried out [32]. This resulted in development of a new "Fracture Zone Identifier" or FZI attribute. This new technology, providing a better understanding of the fracture network, was extended to the unconsolidated sediment environment at North Brawley but the initial work did not immediately accomplish the objective of a significant increase to the full capacity (50 MW) production. We will further elaborate on this technical study and highlight additional work to be done to reach that objective in sections 5.1 and 5.2.

4.2 *Concerns about seismicity and subsidence*

Extraction of geothermal fluids, like other processes that extract large quantities of fluid from deep underground, can cause concerns about subsidence and decreased stability of land, as well as raising concerns about the possibility of triggering small earthquakes that may in turn have a small probability of setting off larger quakes [4, 33]. The type of generation requiring an EGS has a higher risk than some other methods of inducing seismicity, as this process involves forcing fluid underground to propagate cracks in the rock [4]. An examination of induced seismicity concerns was conducted by the Committee on Induced Seismicity Potential in Energy Technologies et al. [33]. It concluded that hydraulic fracturing

DOI: 10.7569/JSEE.2014.629512

(or hydroshearing as the process term has been established in the geothermal literature) posed only a small risk of triggering a seismic event large enough to be felt, and that disposal of waste water by reinjection to the ground does pose some risk of inducing seismicity but very few events have been documented over the years in comparison to the large number of reinjection sites. However, extraction and reinjection of underground fluids in the Salton Sea region has raised concerns that seismic events could possibly be induced, and this in turn has raised concerns about the possibility for seismic events in Imperial Valley to trigger a quake along the San Andreas fault. This is still an active area of investigation [34].

Some farmers in Imperial Valley have voiced concerns that nearby geothermal developments are causing their land to subside, negatively affecting irrigation channels and thus farming production in the area [35]. The concerns about induced seismicity and subsidence, real or perceived, in Imperial Valley and elsewhere will continue to be addressed (substantiated or refuted) through more studies with more monitoring stations. Examples of such work are highlighted in section 5.2.

4.3 Competition from other technologies

Geothermal is in competition with other electricity generation technologies. If these technologies offer better returns, then they will be preferred by investors. Rose et al. [2] considered that the cost of generating electricity from geothermal sources in Imperial Valley would be $30/MWh in 1978 dollars, which would be $94/MWh in 2013 dollars (adjusted using PPI index data from the Bureau of Labor Statistics [36]).

In 2006, ORMAT entered into a Power Purchase Agreement (PPA) with Southern Edison to sell electricity from its Ormesa, Heber 1, and Heber 2 geothermal plants in Imperial Valley for about $62/MWh ($74 in 2013 dollars) [37]. After this expired in 2013, ORMAT entered a 10-year agreement (regarding one of these plants, Heber 1, previously entered into the 2006 PPA) to sell electricity for $86/MWh [38]. The wholesale prices received for selling power in both cases are less than Rose et al. [2] considered it would cost to generate electricity from these geothermal sources. If sale prices this low had been predicted by the Rose et al. study, it is likely that geothermal would not have been considered as much of a beneficial option to the region as projected, as the cost of generating electricity is higher than the price received when selling it.

In 2006, a report by the Western Governors' Association (WGA) considered there to be over 1000 MW of geothermal in Imperial Valley that could be developed for a levelized cost of $80/MWh ($95 in 2013 dollars). A more recent evaluation of geothermal generation costs specifically in the Salton Sea area predicted that electricity could be generated for between $90 and $120 per MWh [14]. It should be noted that the WGA study considered several fields, whereas the IID study focused on Salton Sea. Both of these are generally in line with the original price predictions used by Rose et al. [2] when evaluating economic impacts of

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Figure 4 Average wholesale price of electricity in California at CAISO trading hub SP15-EZ from 2008 to 2013 [39].

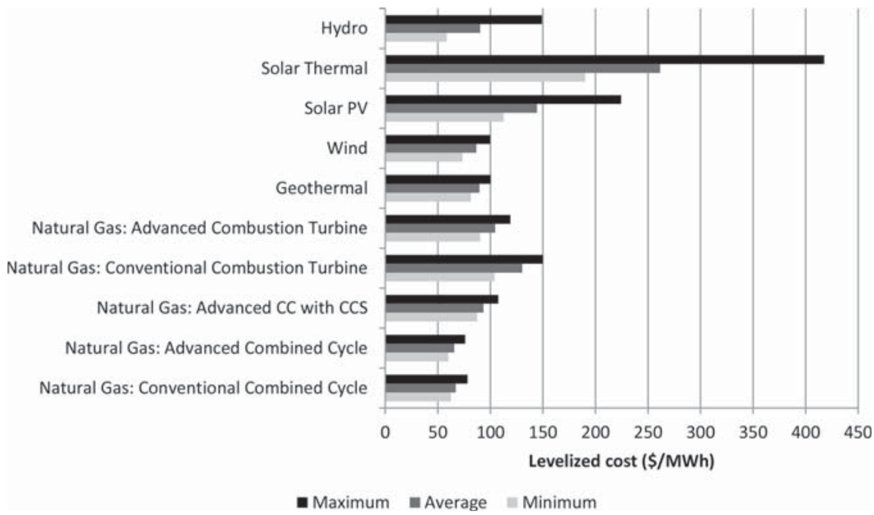

Figure 5 Predicted levelized costs, by technology, expected for generation brought online in the year 2018 [40].

geothermal in Imperial Valley. However, data available on the EIA website indicate that electricity wholesale prices have recently been lower than the expected generation cost of geothermal, at around $50/MWh (Figure 4). This is significantly lower than predicted levelized costs of generating electricity from geothermal plants. One major reason is that the levelized costs of natural gas plants continue to be low (see Figure 5 for recent price projections).

DOI: 10.7569/JSEE.2014.629512

4.4 Transmission limitations

One reason for lack of further geothermal development may be inability to sell any more electricity than is already generated in Imperial Valley, which could be caused by limited capacity of transmission lines that would export the electricity outside Imperial Valley. Summit Blue Consulting, [41] found that the total export capacity from Imperial Valley to the Western Interconnection was 1380 MW. Of this, 600 MW was in the south-north CAISO/SCE intertie at Mirage/Devers (path 42), 225 MW was at the CAISO/SDGE intertie at the Imperial Valley substation, 135 MW was at the APS intertie at the Yucca substation, and 275 MW was at the WAPA Path 9 intertie with Western Power Administration. Local demand is largely met by hydro and other sources. Imperial Valley is considered to be rich in renewable resources, including solar as well as geothermal. A 1380 MW constraint on exports suggests that development of resources could be constrained, because the electricity generated could not be transmitted out of the Imperial Valley. Certainly, with a constraint of 1380 MW of export capacity, the 4500 MW predicted could not have been developed regardless of technical issues and electricity prices available.

5 Assessment of the relative limitations on geothermal development

5.1 Technological advances and economic viability

As discussed above, conventional geothermal resources can experience moderate growth with the emergence of new technologies. As an example, the FZI method was developed [32] for improved assessment of the permeability distribution in the Brawley field (section 4.1). At North Brawley, the application provided an improved understanding of the subsurface sedimentary permeability distribution and its stress field. This information can be used to optimize the location of injection and production well target zones for drilling to maximize the steam production and consequently electricity production.

Figure 6a shows the location of the wells used in a recent case study to better characterize the permeability distribution at North Brawley. As permeability determines the ease of extraction of geothermal fluids, it is a critical factor to understand for production. Figures 6b, c, d and e show the distribution of permeability, applying the newly developed FZI attribute at the producer well A, injector well B, producer well C and producer well D, respectively. High "FZI attributes", indicating high permeability show up at two depths of interest (shallow in light grey and deeper in dark grey) for three of the wells at the evaluated property close to the wellbores. For the fourth well, lack of permeability as interpreted through the applied FZI attribute and lack of major discontinuity close to the zone of interest could indicate the primary reason for low observed throughput for that producer.

Likewise, Figure 7a shows an integrated display at depth slice at Z = 1 km showing a sharp change in stress gradient close to a major discontinuity. High FZI values on both flanks of the discontinuity indicate potential contribution of the

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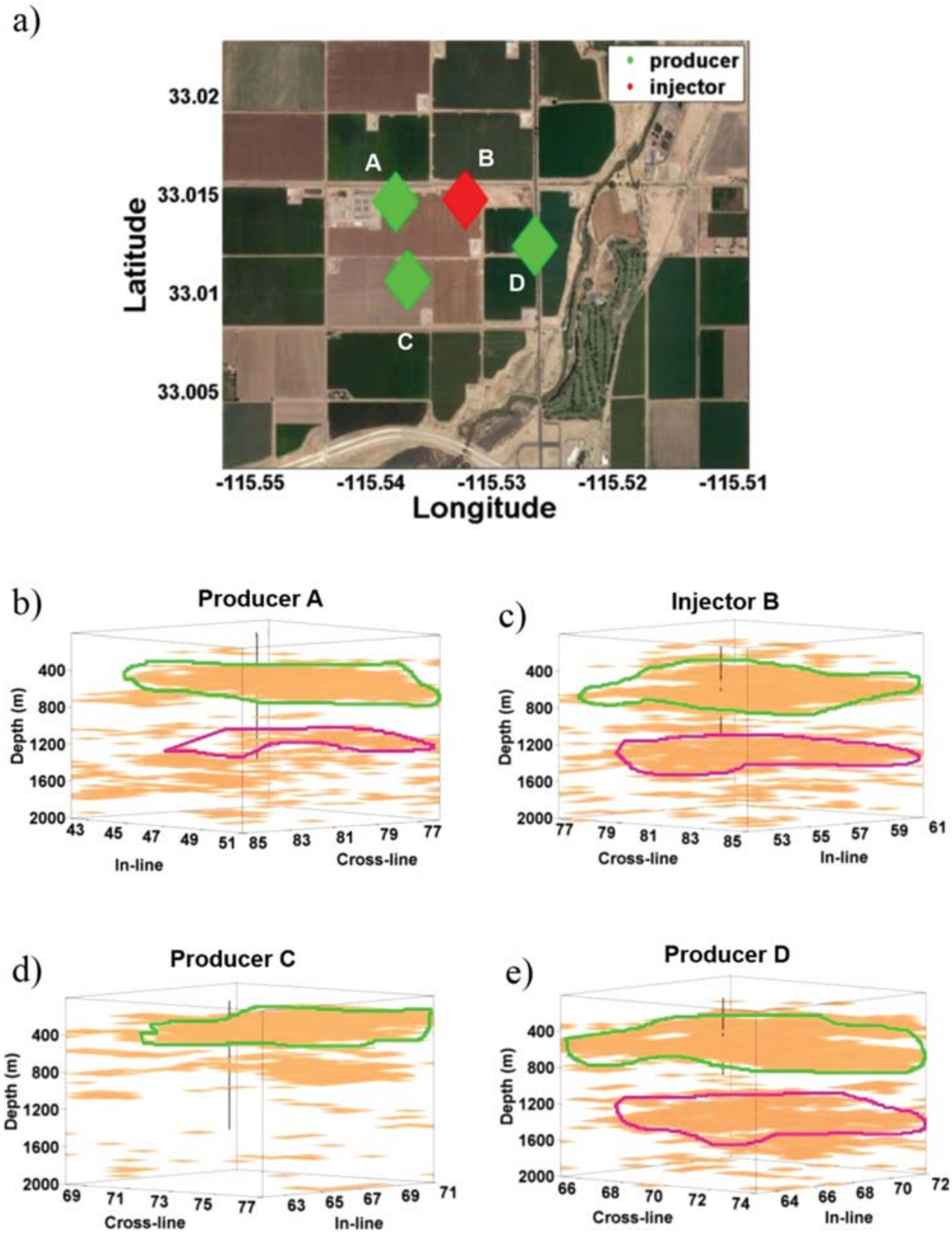

Figure 6 **(a)** location map of the production and injection wells; **(b, c, d, and e)** show the FZI attribute for producers A, C, and D as well as the injector B [32].

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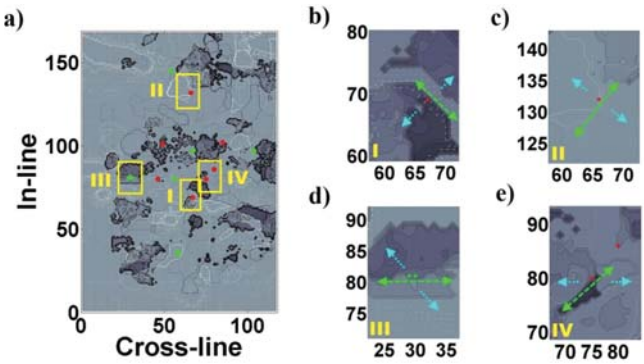

Figure 7 **(a)** integrated display of FZI; **(b, c, d & e)** stress gradient (lighter arrows) and discontinuity boundary (darker arrows) overlaid on the FZI attribute [32].

permeability zone to the well productivity falling on left flank of the discontinuity. The high FZI zone on the right flank could be contributing to well production depending on the specific nature of the discontinuity, i.e., communicating or otherwise. The boxes labeled I, II, III, and IV show the locations of the 4 zones (Figures 7b, c, d and e). The darker arrows indicate discontinuity boundaries and the lighter arrows indicate changes in stress gradient close to the identified boundary location of the wells used in a recent case study to better characterize the permeability distribution [32].

In this particular field, there is potential for further improvements in well target identification by employing a denser seismic monitoring network and expanding surface and borehole seismic arrays using the hybrid acquisition scheme discussed in Maity and Aminzadeh [42].

In the low permeability areas of geothermal fields with brittle rocks, the largest technological improvement step with the potential for one or two orders of magnitude increase in geothermal production would be the use of EGS. Figure 8 displays an EGS model where the potential missing elements of a good geothermal reservoir (fluid and fractures) could be engineered using this technology.

EGS exploits the fact that heat is present almost everywhere at depth. Thus, it can provide emission-free base-load power across the US. Its main components include stimulating a subsurface region via an injection well and opening up fractures in crystalline rock, leading to the creation of geothermal reservoirs thousands of meters below the surface. This is followed up by injecting water through the reservoir and back to the surface in a production well to produce electricity. Although in theory EGS should work, there are many technical challenges that have slowed down progress towards significant increases in geothermal resources. Among those challenges are:

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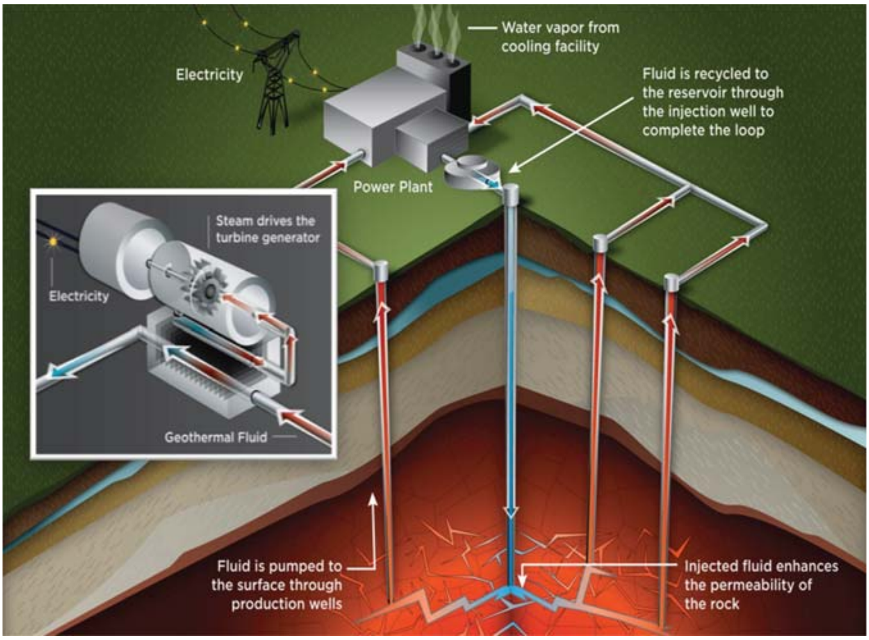

Figure 8 An Idealized EGS Model [30].

- Engineering and managing the geothermal reservoir so that flow rates remain high while thermal drawdown is limited.
- Establishing inter-well connectivity is critical yet difficult to demonstrate.
- Understanding induced seismicity both as a tool and a potential hazard and as such, developing mitigation measures.

In 2011 DOE introduced an ambitious program to help address the above challenges by investing about half a billion dollars in EGS research and development. The USC team received a grant to work on: *Characterizing Fractures in Geysers Geothermal Field by Micro-seismic Data, Using Soft Computing, Fractals, and Shear Wave Anisotropy*. Some of the conclusions of this work were reported by Aminzadeh et al. [43]. Nevertheless, more work needs to be done to fully rectify many outstanding complicated problems. Among the outstanding issues is the economic viability of some of the proposed solutions.

5.2 *Summary of research on induced seismicity and environmental issues*

Concerns about seismicity and hydraulic fracturing operations have prompted creation of induced seismicity consortium (ISC) at USC (isc.usc.edu). The focus of

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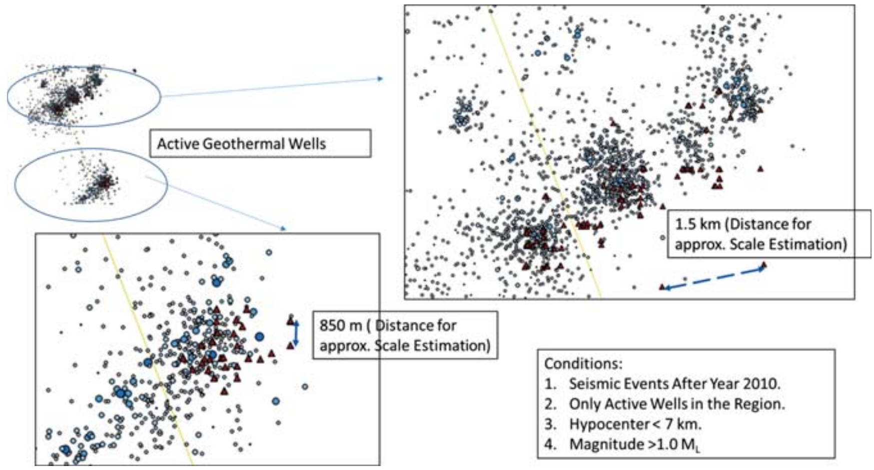

Figure 9 Mapped Earthquakes since 2010 with the active geothermal wells (generated for this article [45]).

ISC has been investigating the impact of hydraulic fracturing and other subsurface fluid injection and production (SFIP) operation both for oil and gas and geothermal fields. A number of methods have been developed to distinguish between induced seismicity and those of tectonics origin, for example Aminzadeh et al. [43] and Aminzadeh and Goebel [44]. Figure 9 shows an example of establishing correlation between geothermal wells and induced seismicity in Imperial Valley. While there are many Magnitude 0 or smaller (small circles) and 1 and 2 (larger circles) seismic events, there is no apparent sizable event. The triangles show the location of geothermal wells.

5.3 Socioeconomic considerations

The socioeconomic progress of Imperial County between 1975 and 2012, in comparison with California and the United States as a whole, is presented in Table 2. Population growth in the County has significantly outpaced that of the two larger regions. The average annual growth in personal income of 6.8% has been nearly as high as that of California and higher than that of the US. However, combined with the County's relatively high population growth, per capita income (PCI) has lagged considerably behind the other two regions. PCI in Imperial County in 1975 was about equal to the national average, but now it is nearly 30% lower. This is offset only slightly by the 10% lower cost of living than the national average. The lag in PCI is even more surprising in Imperial County in light of the large decline in agricultural employment, which typically generates relatively low-wage jobs. PCI in Imperial County is among the lowest 10% of California counties. Gerber [46] attributes this primarily to the relatively low education levels, and to a lesser

DOI: 10.7569/JSEE.2014.629512

Table 2 Socioeconomic Indicators for Imperial County, California, and United States, 1975

	1975			**2012**			
	Imperial County, CA	**California**	**USA**	**Imperial County, CA**	**California**	**USA**	**Source**
Population (persons)	82,989	21,536,715	215,456,585	176,948	38,041,430	313,914,040	BEA
Personal Income (thousands of dollars)	518,339	157,355,533	1,359,998,000	5,466,646	1,768,039,281	13,729,063,000	BEA
Per Capita Income (dollars)	6,246	7,306	6,312	30,894	46,477	43,735	BEA
Cost of Living Index (US Average is 100)				90.0[2]	132.7[2]	100	Census
Total Employment (numbers of jobs)	42,553	10,286,346	98,900,600	73,356	20,653,860	179,613,300	BEA
Farm Employment (numbers of jobs)	10,807	322,528	3,948,000	2,888	218,826	2,616,000	BEA

DOI: 10.7569/JSEE.2014.629512

	1975			2012			
	Imperial County, CA	California	USA	Imperial County, CA	California	USA	Source
Non-farm Employment (numbers of jobs)	31,746	9,963,818	94,952,600	70,468	20,435,034	176,997,300	BEA
Unemployment Rate (percentage)		9.4[3]	8.5	27.2	10.4	8.1	BLS
Avg annual rate of growth in personal income, 1975-2012				6.8	6.82	6.49	BEA
Avg annual rate of growth in employment, 1975-2012				1.53	1.92	1.64	BEA
Avg annual rate of growth in farm employment, 1975-2012				-2.71	-0.78	-1.08	BEA
Avg annual rate of growth in non-farm employment, 1975-2012				2.23	1.98	1.71	BEA

[1] City-Data [47].
[2] Number reflects average level major urban areas in California in 2010.
[3] Nagourney [48].

DOI: 10.7569/JSEE.2014.629512

extent the high (family) dependency rates and low labor force participation rates in the County relative to other regions.

The annual average employment growth of 15.3% in Imperial County between 1975 and 2012 is close to the national average, but the unemployment rate is more than three times the national average. Again, this is explained in part by the much higher rate of population growth in the County. The few hundred additional jobs related to the geothermal industry have helped but have not transformed the regional economy, as was originally projected.

Obviously, the region could benefit from further geothermal development in terms of employment opportunities and those associated with high-paying jobs. However, first it should be noted that extraction and electricity conversion are not labor-intensive industries, so geothermal development would not directly generate as many jobs as would other industries [1]. The indirect (stemming from multiplier) effects of geothermal-related and other industries is likely to be more uniform, as they stem from some common support industries and similar spending patterns among employees. Even greater employment gains could be obtained from industrial applications of geothermal development, such as use in food processing and refrigeration. These applications also represent more efficient use of the resource because the industrial uses channel the downward cascading residual heat from electricity generation, in a form of "co-generation." However, the only industrial application currently in use in Imperial County is aquaculture.

5.4 Observed effects of Policies

Today, the State of California has a Renewables Portfolio Standard (RPS), which requires that 33% of electricity be procured from renewable sources by 2020 [49]. This has been expanded from a previous RPS, which had a 20% renewable source target by 2010. As of 2012, 22% of electricity in California was procured from renewable sources [50].

The expanded RPS target of 33% is expected to be more challenging, as it will require a significant investment in electricity transmission lines over and above the significant upgrade of transmission lines completed in 2010 for the previous target [51]. Imperial Valley has been the subject of considerable discussion with regards to meeting the RPS requirements, as it is rich in both solar and geothermal resources; Imperial County itself is now beginning to focus its identity around renewable electricity generation [52]. The IID has pledged to build up to 1700 MW of geothermal capacity in the Salton Sea region by the early 2030s, in addition to over 830 MW of projects in Imperial currently under development [3, 53], indicating a significant increase in geothermal development in the Imperial Valley is forthcoming. This development will still, however, fall short of the initial 4500 MW projection in addition to occurring past the projected target year of 2020.

Discussions of generating renewable energy in Imperial Valley for use in the rest of California focus around transmission constraints as a major concern [54].

DOI: 10.7569/JSEE.2014.629512

The fact that California's RPS mandates a certain portion of generation be achieved from renewable sources appears to have encouraged developers to install transmission lines to reach areas rich in renewable resources that previously were disregarded as not economically preferable, in addition to encouraging utilities to invest in development of new renewable generation facilities. Thus, the RPS has the potential to stimulate significant new development of existing resources in Imperial Valley and other areas.

New transmission lines to export electricity from Imperial Valley have recently come into operation. In June 2012, San Diego Gas and Electric [55] announced the completion and activation of the new $1.9 billion "Sunrise Powerlink" transmission line, which added a 500 kV transmission line linking Imperial Valley to San Diego [56]. The line will initially carry 800 MW, but will later be upgraded to carry 1000 MW of power [55]. In 2011 the Imperial Irrigation District (IID) announced a plan to increase its transmission capacity from 600 MW to 1600 MW through public-private partnerships [57]. Upgrades are to be performed to the "Path 42" import/export line, and construction is expected to be completed in 2014 [57].

The current rush of activity to expand transmission capacity in Imperial Valley indicates that in the past the Region would have been unable to export the electricity generated if its renewable resources were fully developed. As the RPS policy provides a strong push to increase renewable electricity shares, companies are seeking ways to better access the vast quantity of renewable resources in the Imperial Valley by removing transmission constraints as evidenced by the current rush to expand transmission capacity. In addition to geothermal potential in Imperial Valley, it also has a good solar resource that could be developed [41]. Geothermal could be further stimulated by a new bill, SB 1139, which is proceeding through the California Senate. SB 1139 would amend the RPS to require 500 MW of electricity specifically from geothermal sources by 2025 in an effort to recognize the value of geothermal as a renewable base-load generation technology. Currently, there are concerns that geothermal is not sufficiently valued relative to other renewable technologies which only provide intermittent electricity [58], though it would seem that the RPS has still promoted geothermal energy to an extent.

6 Conclusions

Our findings suggest that the main factors preventing geothermal energy development from reaching its projected target in the Imperial Valley are revised expectations of the quantity and quality of the resource, low electricity prices offered to developers, and transmission constraints. One of the obstacles to future development is being overcome by significant investment in transmission lines that can export the electricity from the Imperial Valley to markets in southwestern California and Arizona. Future development could be enhanced by improvements in technologies used to increase yield of geothermal fields, including micro-seismic monitoring and characterizations of the fractures and their changes over time [59].

DOI: 10.7569/JSEE.2014.629512

California's RPS policy appears to be stimulating investment in transmission and generation capacity within the Region. The new demand for renewable energy created by the RPS appears to have made previously unprofitable investments attractive. The extent to which technology improvements in generation and transmission capacity might also have changed return on investment calculations over time has not been investigated here, but such an investigation could provide an indication of the extent to which policy measures alone have stimulated increased investment in geothermal energy development.

Interestingly, just as the Energy Crisis spurred interest in geothermal energy development in the mid-1970s, concern over a potential climate change crisis has spurred renewed interest in action now. It is not surprising that decisions in a small region are influenced by broader goals, but acceptance by the host region is still a factor in the outcome, as is basic economic viability of the technology in order to attract private investment.

The current research has provided an overview of the situation of geothermal electricity generation capacity in Imperial Valley in a qualitative sense, but has not explicitly quantified the factors impacting on installations. Such a quantification in the future would allow the relative weights of factors to be compared, and would clarify the extent that one factor in particular was primarily responsible for lower than projected installations, or if the effect was due to a balanced combination of factors.

Post-audits can be a valuable way of validating methods to assess projections of renewable energy development. The conclusion here is that the original studies on which geothermal energy in Imperial Valley were based did successfully identify a wide range of pertinent issues, but were not able to accurately quantify them. At the same time, the studies did neglect some major factors, like electricity transmission capacity. They also failed to anticipate changes in US energy policy and the increasing role of climate change policy. But, of course, few energy development assessment/projection methods can anticipate such changes over a 40-year time horizon.

Acknowledgements

We thank Zhenhua Chen for compiling the socioeconomic data included in this paper. We also acknowledge Aditya Tiwari (Former USC Graduate Student, now with National Energy Technology Laboratory, NETL) for creating Figure 9. Some of the work here was supported by the sponsors of USC Center for Geothermal Studies (cgs.usc.edu) and Induced Seismicity Consortium (isc.usc.edu). Finally, we acknowledge valuable comments and input from Joe Iovenitti of Geolpogica (formerly with AltaRock), William Cumming (formerly with Unocal), and Patrick Walsh (of Ormat Technology, the Brawley field operator).

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