Update of the Geothermal Electric Potential in Mexico

Luis C. A. Gutiérrez-Negrín

Mexican Geothermal Association (AGM), Morelia, Mich., Mexico
l.g.negrin@gmail.com

Keywords

Geothermal-electric development, hydrothermal, EGS, potential, reserves, resources

ABSTRACT

The current geothermal resources under exploitation for electric generation in Mexico are of hydrothermal type and contained beneath four geothermal fields with an installed capacity of 958 MW (883 MW as running capacity). These fields produced 6524 GWh of electric energy last year, contributing to 2.4% of the national electric output for public service. Based in some recent assessments, the Mexican geothermal electric potential of hydrothermal origin and temperatures higher than 150°C can be established in 2310 MW. Given its type and temperatures, this potential can be developed with conventional technology. Following the terms suggested by the Australian geothermal code and so reflecting a decreasing grade of confidence, this potential is composed of 125 MW as Proven Reserves in the four fields in operation, 245 MW of Probable Reserves in the same fields and in Cerritos Colorados, 75 MW of Measured Resources in Cerro Prieto, 655 MW of Indicated Resources in 19 identified geothermal zones and 1210 MW of Inferred Resources in another geothermal zones. The theoretical potential of EGS-type geothermal resources has not been yet estimated in Mexico, following the protocol endorsed by the IGA. However, the stored heat in Mexico down to 3 km depth can be assessed in 56,960 EJ at temperatures higher than 150°C, based on an old but reasonable study made at global level. This thermal energy is just a fraction of the total available, and represents a power potential of 5250 MW.

Introduction

The geothermal potential of Mexico has been assessed based on different historical approaches. Two of the first assessments were made by Alonso in 1975, who defined a geothermal electric potential of 4000 MW (cit. by Mercado *et al.*, 1982), and Mercado (1976), who estimated a potential of 13,000 MW. Ten years later Alonso (1985) presented a new estimate defining 11,960 MW composed of 1340 MW of proven reserves, 4600 MW of probable reserves and 6000 MW of possible reserves, while Mercado *et al.* (1985) published their estimate for geothermal resources with temperature below 150°C, resulting in 31,498 MW for low temperature (125°C) and 14,317 MW for intermediate temperature (150°C), being the first ones located at the Mexican Volcanic Belt and the second ones at northern Mexico.

Starting in 2002 the electric research institute (IIE) prepared several estimates on the geothermal potential in Mexico, particularly from low and intermediate temperature resources. Based on a volumetric model applied on 276 thermal sites (1398 superficial manifestations) located in 20 of the 32 states of the country and supplemented by the Montecarlo model, Iglesias and Torres (2003) reported a potential between 77 and 86 EJ with 90% confidence (P90). This amount is equivalent to 21.5-24 x 10^6 GWh_{th}, and corresponds to the heat in place. Last year Iglesias *et al.* (2011) published an update of that estimate, encompassing now 918 thermal sites (1797 superficial manifestations) located in 26 states of the country, and concluded that the heat in place is between 1168 and 1274 EJ (P90), equivalent to 324.4-353.9 x 10^6 GWh_{th}. Calculated underground temperatures using geothermometers for 90% of the manifestations are between 60 and 151°C.

Figure 1. Geothermal fields in Mexico.

The geothermal division of the Comisión Federal de Electricidad (CFE) also published its own estimate last year. It was based on 1380 superficial manifestations, whose subsurface temperatures had been previously calculated by geothermometers, and grouped into three classes: high-enthalpy (>200°C), middle (150-200°C) and low (90-150°C) (Ordaz *et al.*, 2011). They applied a volumetric model (main assumptions for each manifestations were: 1 km^2 in area and 2000 m in thickness, porosity 15%, heat recovering 0.25, conversion factor between 0.18 and 0.11 depending on the temperature range, capacity factor 95% and lifespan 30 years) and presented their results as probable and possible reserves for each temperature rank, as shown in Table 1. They also considered as proven reserves the sum of the next projects programmed or planned in the current geothermal fields plus the assessed potential in the Cerritos Colorados field, which resulted in 186 MW.

Table 1. Possible and probable geothermal reserves estimated by CFE (Ordaz *et al.*, 2011).

Reserves/ Temperature	Low (90-150°C)	Middle (150-200°C)	High (>200°C)	Total
Possible (MW)	850	881	5691	**7422**
Probable (MW)	212	221	1644	**2077**
Total (MW)	**1062**	**1102**	**7335**	**9499**

An independent study commissioned by the Mexican regulatory energy commission (CRE: Comisión Reguladora de Energía) and funded by the IDB, including an estimate on the geothermal potential in Mexico, was published in 2011 too (Hiriart *et al.*, 2011). Regarding the hydrothermal resources, they compiled, analyzed and assessed 20 geothermal zones previously explored by the CFE, which were regarded as of highest interest. Based on the available information, they applied two models, one volumetric (the USGS's *Heat in Place*) coupled to the Montecarlo method, and a gradual decompression model. The latter is a mathematic model, simpler than numeric simulators based on the finite element method, but more complex than the volume models. This was an original approach with specific assumptions about temperature, porosity, density, permeability, area and thickness of the probable reservoir for each geothermal zone. Results for those 20 geothermal zones are 761 MW as the most probable value obtained by the volume-Montecarlo method, and 701 MW from the gradual decompression method.

This paper is mainly based on the more recent of the mentioned studies, but also incorporates some approaches used in other not yet published studies on which the author has been involved. All of those interpretations and results are intended to follow the current version of the Australian geothermal code (AGEG-AGEA, 2010) regarding the definition of geothermal reserves and resources, as well as the applicable terms included in the GEA's guide for reporting geothermal progress and results (GEA, 2010). Of course, such code and guide are applicable to individual geothermal zones or projects, but both represent a suitable framework to estimate regional geothermal potentials more transparently. The information presented here is also compared, when necessary, to the proper definitions included in the protocol to estimate and map the geothermal potential for EGS-type resources (Beardsmore *et al.*, 2010), and in the revised version of the same, endorsed by the International Geothermal Association.

Table 2. Types of geothermal resources, temperatures and uses (Goldstein *et al.*, 2011).

Type	In-situ fluids	Subtype	Temperature Range	Utilization: Current	Utilization: Future
Convective systems (hydrothermal)	Yes	Continental	H, I & L	Power, direct use	
		Submarine	H	None	Power
Conductive systems	No	Shallow (<400 m)	L	Direct use (GHP)	
		Hot rock (EGS)	H, I	Prototypes	Power, direct use
		Magma bodies	H	None	Power, direct use
Deep aquifer systems	Yes	Hydrostatic aquifers	H, I & L	Direct use	Power, direct use
		Geo-pressured		Direct use	Power, direct use

Note: Temperature range: H: High (>180°C), I: Intermediate (100-180°C), L: Low (ambient to 100°C). EGS: Enhanced (or engineered) geothermal systems. GHP: Geothermal heat pumps.

1. Hydrothermal Type Geothermal Potential

The current geothermal resources under exploitation for electric generation in Mexico are of hydrothermal type, continental location and high temperature range, according to the classification by Goldstein *et al.* (2011) reproduced in Table 2. There are also low temperature resources being used mainly in balneology developments. Consequently, the geothermal electric potential for these hydrothermal resources seems to be the most suitable type of geothermal potential in Mexico.

1.1. Proven Reserves

A Geothermal Reserve is defined in the Australian code as "that portion of an Indicated or Measured Geothermal Resource which is deemed to be economically recoverable after the consideration of both the Geothermal Resource parameters and Modifying Factors. These assessments demonstrate (…) that energy extraction could reasonably be economically and technically justified." (AGEA-AGEG, 2010). Proven Reserves are defined as "the economically recoverable part of a Measured Geothermal Resource. It includes a drilled and tested volume of rock within which well deliverability has been demonstrated and commercial production for the assumed lifetime of the project can be forecast with a high degree of confidence. Appropriate assessments and studies have been carried out, and include consideration of and modification by realistically assumed economic, market, legal, environmental, social and governmental factors. These assessments must demonstrate that (…) extraction of the geothermal energy could reasonably be economically justified" (AGEA-AGEG, 2010).

Based on that definition, and taken into account the current geothermal development in Mexico, geothermal reserves can be defined only in the geothermal fields under exploitation. In this case, these proven reserves correspond to the 'conventional hydrothermal expansion' type of resource included in the GEA's guide and defined as "the expansion of an existing geothermal power plant and its associated drilled area so as to increase the level of power that the power plant produces" (GEA, 2010).

There are in Mexico four geothermal fields in operation (Fig. 1), with the main data presented in Table 3. The Cerro Prieto field, the biggest and oldest in Mexico, still has an installed capacity of 720 MW, but the two oldest units of 37.5 MW, commissioned by 1973 in the sector known as Cerro Prieto-I, have been out of operation since 2011 due to their high specific consumption of steam, combined with the shortage of available steam in the field –which is preferred for supplying the most recent and efficient power units. Then, the national operative capacity has dropped to 883 MW, representing 1.7% of the national installed capacity for public service (52,512 MW as of December 2011). However, the geothermal-electric output represented 2.4% of the national electricity generation in 2011 (estimated at 258.8 TWh).

CFE is planning to increase the installed capacity in three of the geothermal fields. Including the almost completed units in Los Humeros, further geothermal projects reported in the CFE's master plan (CFE, 2011) known as POISE (Programa de Obras e Inversiones del Sector Eléctrico), are Cerro Prieto V (100 MW) by 2017, Los Azufres III (50 MW) by 2014, Los Azufres IV (25 MW) by 2018 , and Los Humeros III (50 MW) by 2015. The same plan indicates that some of the oldest geothermal plants are to be dismantled, totaling 150 MW by 2020. The projected expansion projects and decommissioning units are presented in Table 4.

Table 3. Main data of geothermal fields in operation in Mexico in 2011.

Data/Field	Cerro Prieto	Los Azufres	Los Humeros	Las Tres Vírgenes	Total
Installed capacity (MW)	720	188	40	10	958
Power units (number)	13	14	8	2	37
Running capacity (MW)	645	188	40	10	883
Running power units (number)	11	14	8	2	35
Electric output in 2011 (GWh)	4547	1576	355	47	6524
Capacity factor (%)	72.1	95.7	101.3*	53.2	77.7
Production wells (number)	172	39	23	4	238
Injection wells (number)	16	6	3	1	26
Steam production in 2011 (million tons)	40.0	14.8	5.1	0.6	60.4
Brine production in 2011 (million tons)	64.2	5.0	0.6	2.0	71.7

* The capacity factor reported for Los Humeros can seem odd, since is higher than 100%, but it only reflects the fact that the eight 5-MW each back-pressure units installed in the field were temporarily operated at a rate higher than their nominal capacity plate, taking advantage of the available steam intended to feed two additional, 25-MW condensing units that are about to be commissioned there.

Source: Based on data from CFE (2012).

Table 4. Proven geothermal reserves in Mexico.

Field	Project (and Planned Date of Commissioning)	Under Construction or Planned Capacity (net MW)		
		New	Retirements	Additional
Cerro Prieto	Cerro Prieto V (2017)	100	75	25
Los Azufres	Los Azufres III (2014)	50	20	30
	Los Azufres IV (2018)	25	15	10
Los Humeros	Los Humeros II (2012)	50	15	35
	Los Humeros III (2015)	50	25	25
Total		**275**	**150**	**125**

Source: Based on data from POISE (CFE, 2011).

Consequently, the proven reserves in Mexico are composed of the additional capacity to be installed after discounting the planned retirements, which according to Table 4 are 125 MWe. These proven reserves correspond to the GEA's category 'conventional hydrothermal expansion'. Several of them (Los Humeros II, Los Azufres III) are in Phase IV (Resource Production and Power Plant Construction) in terms of the GEA's development phase, and the remaining fall in Phase III (Permitting and Initial Development).

1.2. Probable Reserves

This type of geothermal reserve is defined as "the economically recoverable part of an Indicated or in some circumstances, a Measured Geothermal Resource. It will differ from Proven Geothermal Reserves because of greater uncertainty, usually in terms of factors that impact the recoverability of thermal energy such as well deliverability or longevity of the project. There will be sufficient indicators to characterize temperature and chemistry but may be less direct measures indicating the extent of the Geothermal Resource, within economically feasible drilling depth. Appropriate assessments and studies will have been carried out, which include consideration of and modification by realistically assumed drilling, economic, legal, environmental, social and governmental factors. These assessments will demonstrate (…) that commercial energy extraction could reasonably be justified" (AGEA-AGEG, 2010).

In terms of the GEA's guide, probable reserves in Mexico are equivalent to the category 'conventional hydrothermal (produced resource)', defined as "the development of a geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity and where development of the geothermal reservoir has previously occurred to the extent that it currently supports or has supported the operation of geothermal power plant(s)" (GEA, 2010).

The following estimate of probable reserves includes also geothermal projects reported in the current version of the POISE (CFE, 2011), but regarded with a greater uncertainty arising from both, some technical or non-technical uncertainties that must be resolved. These projects are the following: Nuevo León I (50 MW), Nuevo León II (25 MW) and Saltillo (50 MW) to be installed in Cerro Prieto and reported in the POISE as at pre-feasibility stage; Los Azufres V (75 MW) planned by 2020; and the Cerritos Colorados project (75 MW) reported also at pre-feasibility stage. In terms of the GEA's development phase, all these projects can be considered in Phase III (Permitting and Initial Development).

The probable geothermal reserves in Mexico can be defined as 245 MW, resulting from the sum of the new planned projects minus the projected decommissioning of the low-pressure unit 5 of Cerro Prieto-I. Most of these probable reserves correspond to the GEA's category

Table 5. Probable geothermal reserves in Mexico.

Field	Project (and Planned Date of Commissioning)	Planned Capacity (net MW)		
		New	Retirements	Additional
Cerro Prieto	Nuevo León I (no date)	50	30	20
	Nuevo León II (no date)	25	0	25
	Saltillo (no date)	50	0	50
Los Azufres	Los Azufres V (2020)	75	0	75
Cerritos Colorados	Cerritos Colorados (no date)	75	0	75
Total		**275**	**30**	**245**

Source: Based on data from POISE (CFE, 2011).

'conventional hydrothermal expansion', as is the case of the Cerro Prieto and Los Azufres projects, but the Cerritos Colorados project belongs to the category 'conventional hydrothermal (unproduced resource)'.

1.3. Geothermal Resources

The Australian code defines a geothermal resource as "a Geothermal Play which exists in such a form, quality and quantity that there are reasonable prospects for eventual economic extraction. If there is no reasonable prospect for eventual economic extraction then the energy in question should not be included in estimates of Geothermal Resources. The location, quantity, temperature, geological characteristics and extent of a Geothermal Resource are known, estimated or interpreted from specific geological evidence and knowledge. Geothermal Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories." Geothermal Play is just an informal qualitative term denoting an accumulation of heat contained in rocks and/or fluids within the Earth's crust (AGEA-AGEG, 2010).

Measured Resources are further defined as the "part of a Geothermal Resource which has been demonstrated to exist through direct measurements that indicate at least reservoir temperature, reservoir volume and well deliverability, so that Recoverable Thermal Energy (in units of PJ_{th} or MW_{th}-years) can be estimated with a high level of confidence. The Thermal Energy in Place has been demonstrated to exist through direct measurements and assessments of drilled and tested volumes of rock and/or fluid within which well deliverability has been demonstrated, and which have sufficient indicators to characterize the temperature and chemistry. (…) If there is a reasonable basis to do so, convertibility into electricity can be assessed and an additional estimate of the recoverable, converted electrical energy may be stated using units of PJ_e or MW_e-years" (AGEA-AGEG, 2010).

There is a project in Mexico, proposed some time ago for the Cerro Prieto field that seems to fit into that definition. It is the project of using the residual brine currently produced in the field and stored in the solar evaporation pond before injection. The residual brine is at 150°C on average and can be used to feed binary cycle units to produce more than 75 MW (Mañón, 2011, personal communication). There are several technical issues, like the high scaling rate of the brine, that CFE has been attempting to solve, and a comprehensive cost-benefit analysis needs to be done, but the fluids are available at surface and seem to be a typical example for a measured geothermal resource. Based on that, geothermal measured resources in Mexico are considered to be 75 MW, and the project itself would be at the GEA's Phase II (Resource Exploration and Confirmation) of development.

An Indicated Resource is "part of a Geothermal Resource which has been demonstrated to exist through direct measurements that indicate temperature and dimensions so that Recoverable Thermal Energy (in units of PJ_{th} or MW_{th}-years) can be estimated with a reasonable level of confidence. Thermal Energy in Place has been estimated through direct measurements and assessments of volumes of hot rock and fluid with sufficient indicators to characterize the temperature and chemistry. Direct measurements are sufficiently spaced so as to indicate the extent of the Thermal Energy in Place. Assumptions made in making the estimate must be stated, especially in respect of the Base and Cut-off temperatures and the technology pathway for usage. If there is a reasonable basis to do so, convertibility into electricity can be assessed and an additional estimate of the recoverable, converted electrical energy may be stated using units of PJ_e or MW_e-years (…)" (AGEA-AGEG, 2010).

Table 6. Indicated geothermal resources in Mexico.

Geothermal Zone, State	Assessed Potential (MW)			Assigned Value (MW)
	Volumetric Model		Decom-pression Model	
	Probable Value	Range (P90)		
Zones at Estimated Temperature > 180°C				
1. Graben de Compostela, Nayarit	105	35 – 175	110	110
2. Las Planillas, Jalisco	70	26 – 113	83	80
3. Volcán Ceboruco, Nayarit	74	34 – 113	50	65
4. Volcán Tacaná, Chiapas	60	21 – 99	52	60
5. La Soledad, Jalisco	52	10 – 94	51	50
6. Volcán Chichonal, Chiapas	46	9 – 84	45	45
7. Hervores de la Vega, Jalisco	45	20 – 71	45	45
8. Pathé, Hidalgo	33	6 – 61	49	40
9. Cuitzeo Lake (Araró), Michoacán	21	5 – 37	32	25
10. Los Hervores-El Molote, Nayarit	36	12 – 59	17	25
11. Los Negritos, Michoacán	24	3 – 44	20	20
12. Ixtlán de los Hervores, Michoacán	17	0 – 23	15	15
13. El Orito-Los Borbollones, Jalisco	11	1 – 21	9	10
14. Santa Cruz de Atistique, Jalisco	12	2 – 22	13	10
Total	**606**		**591**	**600**
Zones at Estimated Temperature 150-180°C				
1. San Antonio El Bravo, Chihuahua	27	10 – 43	36	30
2. Puruándiro, Michoacán	10	3 – 17	12	10
3. San Bartolomé de los Baños, Guanajuato	7	3 – 12	9	10
4. Santiago Papasquiaro, Durango	4	1 – 7	4	4
5. Maguarichic, Chihuahua	1	0.2 – 1.7	1	1
Total	**49**		**62**	**55**

Source: Adapted from Hiriart et al. (2011). Data of the assessed potential are taken from the reference.

The geothermal potential presented in the CRE's report published last year, fits well into that definition, with some slight adjustments. Departing from the original 20 geothermal zones assessed by Hiriart *et al.* (2011), and taking into account their particular features, 14 of them are here considered as containing high temperature resources (>180°C), able to be developed with condensing (flash) power plants, and 4 more are regarded as intermediate temperature (150-180°C) (Table 6) that can be developed by installing binary-cycle power plants. The remaining zone (Acoculco, state of Puebla) is not included in the following estimate, because it appears not to be a hydrothermal zone.

Thus, the indicated geothermal resources in Mexico can be defined as 655 MW, composed of 600 MW of probable high temperature resources and 55 of intermediate temperature. According to the GEA's guide, these resources are 'conventional hydrothermal (un-produced resources)', and all the enlisted zones are in the Phase I (Resource procurement and identification) of development.

The Australian code defines an Inferred Resource as "that part of a Geothermal Resource for which Recoverable Thermal Energy (in units of PJ_{th} or MW_{th}-years) can be estimated only with a low level of confidence. Assumptions made in making the estimate must be stated, especially in respect of the Base and Cut-off Temperatures and the technology pathway for usage. If there is a reasonable basis to do so, convertibility into electricity can be assessed and an additional estimate of the recoverable, converted electrical energy may be stated using units of PJ_e or MW_e-years. The recovery and conversion (if used) factors used must be separately stated alongside the Geothermal Resource figure, whenever it is quoted in a Public Report. This category of Geothermal R esource is inferred from geological, geochemical and geophysical evidence and is assumed but not verified as to its extent or capacity to deliver geothermal energy. There must be a sound basis for assuming that a Geothermal Play exists, estimating the temperature and having some indication of its extent" (AGEA-AGEG, 2010).

The estimates made by Ordaz *et al.* (2011) for their category of probable reserves of high (>200°C) and intermediate (150-200°C) temperature (Table 1) seem to fit into the above definition. They got 1644 MW for high temperature and 221 MW for intermediate temperature, but it must be taken into account that these numbers include the geothermal potential of all of the 19 zones listed in the Table 6. Therefore, to define the remaining potential that can be deemed as Inferred Resources, it is necessary to discount the already mentioned Indicated Resources. Then, inferred resources of high temperature would be: 1644 MW (Table 1) – 600 MW (Table 6) = 1,044 MW, and inferred resources of intermediate temperature would result: 221 MW (Table 1) – 55 MW (Table 6) = 166 MW.

Based on that assumption, the Inferred Resources in Mexico can be estimated in 1210 MW, composed of 1044 MW of high temperature (>180°C) able to be developed through flash power plants, and 166 MW that can be used by installing binary cycle plants. This inferred potential is composed of a number of superficial manifestations and geothermal zones along the country, excepting the 19 zones presented in Table 6 and regarded as Indicated Resources.

The Inferred Resources correspond also to the 'conventional hydrothermal (un-produced resources)' category of the GEA's guide, and excepting a few most of them does not reach even the GEA's Phase I of development.

2. Hot Dry Rock (EGS) Potential

The proper way to estimate in Mexico the geothermal potential from hot dry rock resources, developable with EGS technologies, is the procedure outlined by Beardsmore *et al.* (2010) in their Protocol to do that, which has been reviewed and endorsed by the IGA. This is a pending matter that eventually will be done, but in the meantime it is worth to have a preliminary idea about that potential, just to complement the mid-high temperature hydrothermal potential above mentioned.

There are not much publicly available data on heat flow in Mexico. Prol-Ledesma (1991) published 53 direct heat flow measurements using the conventional method (based on the Fourier equation) in some oil exploration wells and mines scattered in the country, and got minimum of 13 and maximum of 191 mW/m^2. In her paper, Prol-Ledesma (1991) also reported some other heat-flow data obtained in 1986 by applying the silica geothermometer on 326 hot springs located in the central, south and northwestern regions of Mexico, and presented a map showing the estimated equilibrium temperatures and the values of heat-flow obtained.

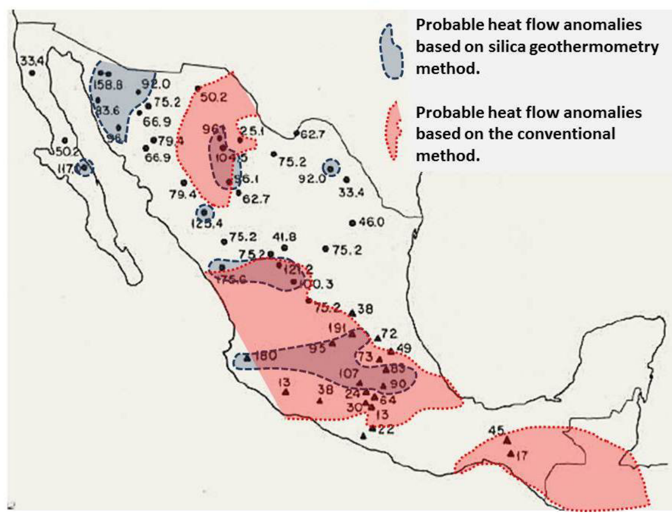

Figure. 2. Probable heat-flow anomalies in Mexico (adapted from Prol-Ledesma, 1991).

Figure 2 shows the map with the original heat flow data obtained by Prol-Ledesma (1991) applying the silica geothermometer method, on which the probable heat-flow anomalies (>80 mW/m^2) have been outlined in blue. The probable heat-flow anomalies of the values obtained from the conventional method are also superimposed in red. The data, of course, are too scattered to try to define heat-flow provinces in the country, as it has been remarked (García, 1989; Prol-Ledesma, 1991). But even so, it is possible to infer some two or three zones with high heat-flow values where both 'anomalies' coincide, which at the moment would be the most interesting zones in Mexico regarding heat-flow. Among them is the northern zone that seems to be linked to the southern prolongation of the Rio Grande rift zone, with high heat-flow values in the US, the central zone probably related to the Mexican Volcanic Belt, the northwestern zone (in blue) perhaps related to the Basin and Range province, and the southeastern zone probably due to the subduction of the Cocos Plate along the Mid-American Trench (Prol-Ledesma, 1991).

It is worth to mention that there are also some heat-flow estimates derived from the Helium isotopic relation, made by Polak *et al.* (1985) on 22 samples collected from hot springs mostly located in the central part of Mexico. Highest heat-flow values fall into the central zone.

On the other hand, in 1978 the Electric Power Research Institute made an estimate of the global heat stored down to 3 km depth, country by country, based on several reasonable assumptions about the normal and anomalous thermal gradients, the specific volumetric heat and the ambient temperature. Then, they applied the equation: Q = (A) (H) (Cv) (T-15), where Q is the thermal energy, A is the area, H the thickness, Cv the specific heat and T the temperature (EPRI, 1978).

For Mexico, the EPRI assumed that 60% of the territory is within one or more of the so called ‘thermal belts’, related to the plate borders and where the vertical thermal gradient is higher than the average. They then reported that the stored heat beneath the country up to 3 km depth is about 71,200 EJ at temperatures ≥150°C, composed of 67,000 EJ between 150 and 250°C and 4200 EJ at temperatures >250°C (EPRI, 1978; also cited by Hiriart *et al.*, 2011).

According to the EPRI assumptions, 20% of that stored heat would be of hydrothermal type (stored in fluids) and 80% of hot dry rock type. Then the stored heat in Mexico for EGS-type resources at temperatures >150°C and down to 3 km depth would be: 71,200 x 0.8 = 56,960 EJ.

It is important remark those 56,960 EJ do not mean a Theoretical Potential, according to the referred Protocol. Theoretical Potential, as defined by Rybach (2010) and adopted in the Protocol, is “the physically usable energy supply over a certain time span in a given region. It is defined solely by the physical limits of use and thus marks the upper limit of the theoretically realizable energy supply contribution” (Beardsmore *et al.*, 2010). Then, the theoretical potential is simply the upper limit of what can be produced from an energy resource based on physical principles and current scientific knowledge. However, to estimate it, the Protocol recommends a sequence of steps to get first the available heat in the Earth’s crust down to 10 km depth. Then a subsequent series of steps are recommended to reach the Theoretical Potential in terms of H (the total available thermal energy in EJ) and then to derive the Theoretical Potential in potential power (MW_e). This Theoretical Potential is estimated between 3 and 10 km depth, excluding the first 0-3 km depth (assumed as the sedimentary layer): “For consistency with existing EGS maps of the USA, EGS potential should be estimated for the midpoint of every 1,000 m thickness interval between 3,000 m and 10,000 m depth, excluding intervals of Sediment. That is, Theoretical Potential should only be estimated within the Basement section” (Beardsmore *et al.*, 2010).

Thus, in the best case, the estimate presented here would be partially equivalent to the first part of the procedure suggested in the Protocol, and barely can be regarded as a theoretical potential, not to mention a technical potential. Therefore, the estimate of 56,960 EJ would be equivalent to a part of the total available thermal energy in Mexico. Anyway, perhaps the result of this exercise can give a first idea about the magnitude of the actual EGS-theoretical potential in Mexico.

A simple approach to convert that part of the total available heat into potential power, is assume that 2% of it can be recovered, that average temperatures drop 10°C below initial conditions during exploitation, and take into account standard losses in the conversion of recoverable heat into electricity over a lifespan of 30 years at a capacity factor of 90%. Under such assumptions, the rough equivalence is 1 x 10^6 EJ of stored heat equals approximately 2.61 EJ/yr of technical potential for electricity, or 725 TWh/yr of electric energy. Then, 0.05696 x 10^6 EJ of stored heat is roughly equivalent to 0.149 EJ/yr or 41.39 TWh/year. This electric output could be produced by 5250 MW of installed capacity at an annual capacity factor of 90%. And then, from this simple approach, 56,960 EJ of stored heat would be equivalent to 5250 MW.

3. Conclusions

Present installed geothermal-electric capacity in Mexico is 958 MW, although the effective or running capacity is 883 MW because of two old 37.5-MW power units in Cerro Prieto were put out of operation in 2011. Geothermal-electric output in 2011 was 6524 GWh, at a national annual capacity factor of 77.7%. Geothermal represented 1.7% of the electric capacity in Mexico for public service in 2011, and 2.4% of the country’s electric output. 238 production and 26 injection wells were in operation in the four geothermal fields, with a steam output of 60.4 million tons accompanied by 71.7 million tons of brine.

Taking into account recent estimates of the geothermal electric potential in Mexico, it is possible to conclude that it can be defined as 2310 MW from high- and intermediate-temperature (>150°C) hydrothermal resources and at least 5250 MW from high- and intermediate-temperature (>150°C) EGS-type resources.

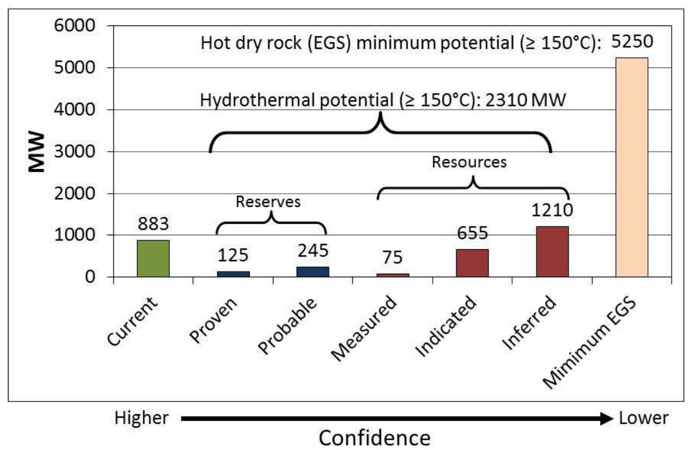

Figure 3. Geothermal potential in Mexico from resources at ≥150°C of temperature.

The hydrothermal potential is composed of 125 MW of Proven Reserves, 245 MW of Probable Reserves, 75 MW of Measured Resources, 655 MW of Indicated Resources and 1210 of Inferred Resources, according to the terminology defined by the Australian geothermal code (Fig. 3).

The technical potential from EGS-type resources has not been properly estimated, according to the protocol proposed by Beardsmore *et al.* (2010) and endorsed by the IGA. The estimate presented here, amounting 5260 MW, is a simple approximation that can be regarded only as a small part of the actual theoretical potential, but still can give a general idea about its magnitude.

References

AGEA-AGEG, 2010. *The Geothermal Reporting Code, Second Edition (2010)*. Publication of the Australian Geothermal Reporting Code Committee of the Australian Geothermal Energy Association (AGEA) and the Australian Geothermal Energy Group (AGEG), 34 p.

Alonso, H., 1985. Present and planned utilization of Geothermal Resources in Mexico. *Geothermal Resources Council Transactions*, Vol. 9, pp. 135-140.

Beardsmore, G.R., L. Rybach, D. Blackwell and C. Baron, 2010. A protocol for estimating and mapping global EGS potential. *Geothermal Resources Council Transactions*, Vol. 24, pp. 301-312.

CFE, 2011. Programa de Obras e Inversiones del Sector Eléctrico 2011-2025. Comisión Federal de Electricidad, Subdirección de Programación, Coordinación de Planificación, 312 pp. Available at: www.cfe.gob.mx.

CFE, 2012. Internal data on geothermal fields from the geothermal division of CFE. Unpublished.

EPRI, 1978. *Geothermal energy prospects for the next 50 years*. Special Report No. ER-611-SR of the Electric Power Research Institute for the World Energy Conference. 104 pp.

GEA, 2010. New Geothermal Terms and Definitions. Publication of the Geothermal Energy Association, 17 p. Available at: www.geo-energy.org.

García-Estrada, G., 1989. Las técnicas de medida de flujo térmico en continentes, métodos opciones y su aplicación en México. *Geotermia*, Vol. 5. No. 3, pp. 375-410.

Goldstein, B., G. Hiriart, R. Bertani, C. Bromley, L. Gutiérrez-Negrín, E. Huenges, H. Muraoka,A. Ragnarsson, J. Tester, V. Zui, 2011. Geothermal Energy. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K.Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hiriart Le Bert, G., L.C.A. Gutiérrez Negrín, J.L. Quijano León, A. Ornelas Celis, S. Espíndola e I. Hernández, 2011. *Evaluación de la Energía Geotérmica en México*. Report for the Interamerican Development Bank (IDB) and the Energy Regulatory Commission (CRE). Mexico City, May 2011. Available at: http://www.cre.gob.mx/articulo.aspx?id=384.

Iglesias, E.R. and R.J. Torres, 2003. Low- to medium-temperature geothermal reserves in Mexico: a first assessment. *Geothermics*, 32, pp. 711-719.

Iglesias, E.R., R.J. Torres-Rodríguez, J.I. Martínez-Estrella, y N. Reyes-Picasso, 2011. Resumen de la evaluación 2010 de los recursos geotérmicos mexicanos de temperatura intermedia a baja. *Geotermia*, Vol. 24, No. 2, pp.

Mercado, S., 1976. The Geothermal Potential Evaluation of Mexico by Geothermal Chemistry. *Proceedings of the International Congress on Thermal Waters, Geothermal Energy and Volcanism of the Mediterranean Area*. Athens, Greece, 1976.

Mercado, S., V.M. Arellano, R.M. Barragán, R. Hurtado, D. Nieva, E. Iglesias, G. Barroso y H. Fernández, 1982. Diagnósticos y Pronósticos Sobre los Aspectos Científicos y Tecnológicos de la Geotermia Como Fuente de Energía en México. Internal report No. IIE/CFE-G37/1767/3. Unpublished.

Mercado, S., J. Siqueiros, and H. Fernández, 1985. Low Enthalpy Geothermal Reservoirs in Mexico and Field Experimentation on Binary-Cycle Systems. *Geothermal Resources Council Transactions*, Vol. 9, pp. 523-526.

Ordaz Méndez, C.A., M. Flores Armenta and G. Ramírez Silva, 2011. Potencial geotérmico de la República Mexicana. *Geotermia*, Vol. 24, No.1, pp. 50-58.

Polak, B.G., V.I. Kononov, E.M. Prasolov, I.V. Sharkov, R.M. Prol-Ledesma, A. González, A. Razo, and R. Molina-Berbeyer, 1985. First estimations of terrestrial feat flow in the TMVB and adjacent areas based on isotopic composition of natural helium. *Geofísica Internacional*, Special volume on Mexican Volcanic Belt, S.P. Verma, ed., Vol. 24, No. 3, pp. 465-476.

Prol-Ledesma, R.M., 1991. Terrestrial heat flow in Mexico. In: *Exploration of the Deep Continental Crust*, V. Cermák and L. Rybach, eds., Springer-Verlag Berlin Heidelberg, Berlin, pp. 475-485.

Rybach, L., 2010. The future of geothermal energy and its challenges. *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25–29 April 2010.