ELECTRIC POWER POTENTIAL ESTIMATES OF HIGH-TEMPERATURE GEOTHERMAL FIELDS IN INDONESIA AND THE PHILIPPINES (A HISTORICAL REVIEW)

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Keywords: *power potential estimates, volume (stored-heat) method, historic assessments, predicted potential versus present-day running capacity, predicted levelized costs of electricity*

ABSTRACT

Electric power potential (Pe) estimates have been used between 1975 and c. 2000 for the initial development of 15 presently producing geothermal fields in Indonesia and the Philippines. Most estimates were based on stored (useable) heat assessments using the stored heat-volume method and data from flow-tested exploratory wells. Many early estimates were checked later by using numerical modelling and simulation methods. Comparison between recent running field capacities (Crf) and lapse-time Pe data shows that most Crf data are approaching earlier and revised Pe values after 10 to 25 yrs of field operation.

However, the stored heat-volume method may lead to overestimates of Pe under certain conditions. Overestimates of early Pe values are indicated for a few Philippine fields associated with concealed reservoir outflow structures. The potential of a developed volcanic geothermal system in Indonesia has been overestimated since sectors with deep corrosive fluids were not excluded. Levelized costs of electricity (LCoE) based on Pe data are not available for the Philippine fields. Such estimates, based on early Pe estimates and using Monte Carlo simulation, were obtained for the Indonesian fields. The lowest costs are indicated for exploited vapour-dominated fields, the highest for fields associated with volcanic geothermal systems.

1. INTRODUCTION

Assessments of the electric power potential (Pe) of high temperature geothermal fields in Indonesia and the Philippines has been used in the past to predict and to modify development of geothermal reservoirs of 15 fields, now under exploitation.

Almost all early Pe estimates were based on the inferred stored anomalous heat of the prospect and the reservoir fluid characteristics obtained from a few flow-tested discovery wells, i.e. the prospects were treated as proven reserves (Pe estimates of 'proven reserves'). Pe estimates of proven reserves were usually calculated for a predicted 30 yr plant life.

Most of the earlier Pe estimates for 8 producing Philippine fields have been presented (Sarmiento and Bjoernsson, 2007) whereas a similar study has not been made for the presently producing 7 Indonesian fields. In a recent assessment of the inferred geothermal potential of Indonesian geothermal prospects (Surya Darma et al., 2010), historic Pe assessments of producing Indonesian fields are not listed. In this study we look at the question whether predictions of earlier Pe estimates were of the right order of magnitude and how they compare with revised estimates of later developments when a significant response of the exploited reservoirs had been observed (later Pe estimates derive from reservoir modelling or are modified by using more representative stored heat data at a certain stage of exploitation, so-called 'brown-field' Pe estimates).

2. PRESENTATION AND COMPARISON OF ESTIMATES

Early Pe estimates of proven reserves are not available for 6 of the 7 presently developed Indonesian geothermal fields, with the exception of the Kamojang field. Other Pe estimates have been kept confidential. However, we could obtain early Pe estimates for a given undeveloped field by using early exploration data up to the period when the resource was proven by deep, flow-tested wells. Such early data have been summarized for Indonesian prospects (Hochstein and Sudarman, 2008). An example for an early Pe estimate of a now producing Indonesian field is listed in Appendix I. The same approach can be used to obtain 'brown-field' Pe estimates when new published reservoir characteristics become available.

Most early Pe estimates of undeveloped fields in the Philippines were upgraded later when the fields had been developed and produced an observable reservoir response. In a few cases of 'aggressive' development one can only use the published plant capacity at a certain time of exploitation to infer the likely order of magnitude of Pe estimates which would have been used to justify extension or reduction of plant capacity.

Assuming that the recently published 'average running field capacity' (Crf) data of fields with a long exploitation history tend to approach economically justifiable field developments, we can compare Pe values of different fields and their Crf data to assess the significance of power potential (Pe) estimates. Present Crf values for Philippine geothermal plants were taken from Ogena et al. (2010). For Indonesian plants recent Crf data have not been published - in this case we use the presently installed plant capacity (Cp) listed in Surya Darma et al. (2010). In Crf versus Pe plots, as shown in Figures 1 and 2, the data points above the Crf = Pe line often indicate Pe over-estimates.

All Pe values for proven and brown-field reserves contain a significant uncertainty which was assessed for early Pe data by assuming standard error propagation. For random errors, the probability distribution of the resulting population of Pe values can be obtained by using a Monte Carlo simulation. Here the mean of Pe has the probability of p = 0.5 and the value at integrated probability bounds (usually p = 0.1 and p = 0.9) can be used for risk assessment (Sarmiento and Steingrimssom, 2008). Early Pe and 'brown-field' Pe estimates of Indonesian fields quoted in this paper were obtained using the Monte Carlo simulation.

3. PREDICTED Pe OF PHILIPPINE GEOTHERMAL FIELDS

Predicted and revised Pe values for 8 developed Philippine fields are shown in Figure 1. The year of a Pe estimate is shown next to the data point. The Pe data are shown for three data groups: i. the early Pe estimates for a proven resource at a time when the resource had been confirmed by flow-tested exploration wells, ii. an upgraded Pe value obtained from later reservoir simulation studies, and iii. an inferred (but unpublished) Pe limit is indicated by the installed plant capacity (Cp). The inferred Pe value for iii. would be a minimum value since capital is invested conservatively, i.e. the expected value (mean) of Pe is higher than the capacity that lenders and equity investors are willing to fund since they are typically risk averse rather than expected value decision makers. Details of Pe estimates for groups i. and ii. can be found in Sarmiento and Bjoernsson (2007), a reference which also shows the location of the fields.

The widest spreads between Pe data with time (time lapse Pe values) have been reported for the Palinpinon, Tiwi, and Mak Ban fields (see Figure1). At Palinpinon, the early Pe estimate of c. 360 MWe in 1978 was an over-estimate since reservoir modelling of the partially developed field in 1990 showed a reduced potential of c. 112 MWe. This, in turn, was an under-estimate since the field performance allowed additional installation of plants with a total running capacity of c. 190 MWe by 1995. The present running capacity is c. 180 MWe. The cause for the initial over-estimate was a misinterpretation of the productive sector of the reservoir affected by extensive concealed thermal outflow structures.

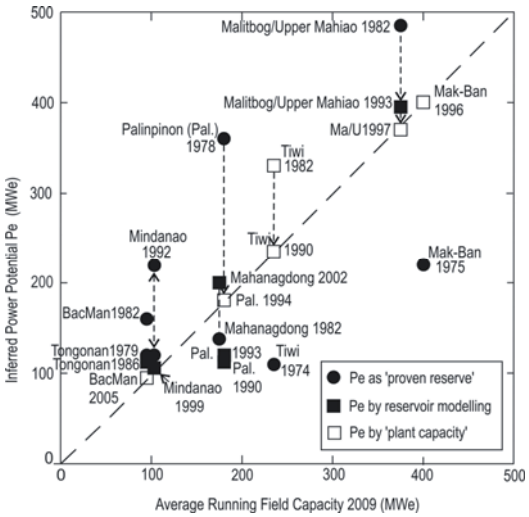


Figure 1: Running field capacity (Crf) versus inferred power potential (Pe) of developed Philippine geothermal fields

At Tiwi the early Pe estimate of c. 110 MWe in 1974 covered a sector with significant active manifestations which was associated with a concealed large outflow structure. The actual setting of the parent reservoir was not recognised. An aggressive development led to the construction of 3 x 110 MWe plants by 1982. Lateral inflow of groundwater after 1982 reduced production and limited the running capacity of the plants. Significant production could be maintained by exploring and exploiting the upstream part of the system. The capacity of the field was downgraded to 275 MWe in 2001. Since then production has been sufficient to supply two plants with a present running capacity of c.235 MWe.

At Mak-Ban the initial Pe estimate in 1975 pointed to a long-term capacity of c. 220 MWe. An outflow structure was recognised from early exploration wells but was not exploited. Our retro-check of the early Pe estimate (using a standard heat recovery factor of 0.25 and a cross-sectional extent of the reservoir of c. 10 km2) yields a similar result. Later upgraded Pe values have not been published for Mak-Ban. Enhanced reservoir management and production-induced natural recharge allowed an increase in the production of hot fluids and lead to a rapid increase of installed plant capacity from 110 MWe in1979 to 330 MWe by 1984. Installation of additional smaller plants in the 1990's increased the total installed plant capacity to c. 425 MWe by 1996. Its present running capacity is c. 400 MWe. Although the output has been declining, the example shows that with proper reservoir management a capacity larger than that early predicted can be reached. From an environmental point of view one could argue that the aggressive development of the

Mak-Ban field is not a model for a sustainable long-term exploitation of a geothermal reservoir.

The time lapse Pe values for the same prospect is smaller for several other exploited Philippine fields. Data are shown in Figure1 for sectors of the large Tongonan to Upper Mahiao to Malitbog field and its nearby separate Mahanagdong field. For the Tongonan field sector an early Pe estimate of c. 120 MWe was quoted in 1979, simple reservoir modelling pointed to a slightly lower value in 1986. Its present Crf capacity is 95 MWe. The early Pe estimate of the combined Upper Mahiao to Malitbog sector was listed as c. 485 MWe in 1982 when it was assessed as a coherent proven resource. The long-term potential was reduced to 395 MWe in 1993 as a result of reservoir modelling, close to its present running capacity of c. 370 MWe. The early Pe estimate for the Mahangdong field was c. 140 MWe in 1982. Reservoir modelling in 2000 pointed to a potential of 200 MWe; its running capacity at present is 175 MWe.

For the BacMan field early Pe estimates of 160 MWe and 150 MWe were quoted in 1982 and 1985 respectively. The field had been developed by 1993 with an installed plant capacity Cp of c. 150 MWe. Turbine and cooling tower problems limited later plant operation; its present day running capacity is c. 95 MWe.

Widely differing Pe values between c. 120 and 220 MWe were quoted for the Mindanao prospect in 1992. The first two plants (54 MWe each) were commissioned between 1996 and 1999. Reservoir modelling in 1999 pointed to a long-term capacity of 105 MWe. The present running capacity is 103 MWe.

The history of electric power potential estimates of nine developed geothermal fields in the Philippines shows that early estimates are only the first step of a continuous assessment process. It is regrettable that many of the later steps have been kept confidential. Apart from two examples of early Pe over-estimates (Palinpinon and Tiwi), most earlier potential estimates of reservoirs at the undeveloped but proven resource state came up with acceptable long-term order of magnitude Pe estimates. However, economic implications of the assessment were not presented.

4. PREDICTED POTENTIAL OF DEVELOPED INDONESIAN FIELDS

Predicted and revised Pe data for 8 developed Indonesian fields are shown in Figure 2. The points refer to three groups of data: i. Pe values for an undeveloped field of proven resource status, ii. Pe values derived from reservoir modelling of a partially developed field, and iii. Pe estimates predicting expansion potential of producing fields (i.e. 'brown-field ' Pe estimates). Our brown-field estimates are based on upgraded reservoir characteristics of the developer (Wayang Windu 1999 and Dieng 2002). The Geological Agency of the Government of Indonesia published additional estimates (Dieng 2010).

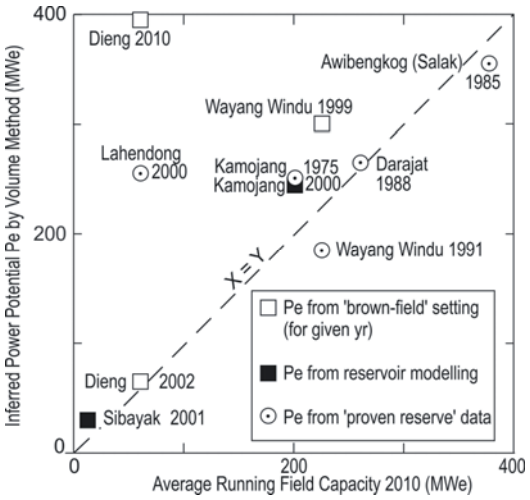


Figure 2: Running field capacity (Crf) versus predicted Pe of producing Indonesian fields

All Pe values in group i. and iii. were obtained using stored heat - volume assessments, though the assumptions used vary from case to case.

An early Pe value of a proven resource was only published for the Kamojang field (Hochstein, 1975). Other early 'retro-checked' Pe values of prospects were obtained for the Awibengkok (Salak) and the Darajat fields using the geophysical data known at the time when the first deep flow-tested wells had confirmed the proven resource. These early survey data have been compiled recently (Hochstein and Sudarman, 2009). An example of a 'retro-checked' early Pe assessment is shown in the Appendix I. A few other points in Figure 2 refer to so-called 'brown-field' (Pe) estimates where known reservoir characteristics of a partially developed field were used as input for the volume-stored heat method to assess the potential of future developments of these fields.

The first Pe estimate for the Kamojang vapour-dominated field in 1975 pointed to a potential between 200 MWe and 275 MWe (when normalized for 30 yr plant life). Using additional deep well information available by 1980, we re-assessed the potential of the field and obtained a Pe of c. 250 MWe (175 MWe at p = 0.05 and 350 MWe at p = 0.95). The first plant with a capacity of 30 MWe was commissioned in 1982, its installed capacity was increased to 140 MWe in 1987. Reservoir modelling in 2000 by Sanyal et al. (2000) pointed to a long-term potential between 210 MWe and 280 MWe. This led to a capacity increase by 60 MWe in 2007 to reach a total of 200 MWe, its present running capacity.

The nearby vapour dominated Darajat field was considered to be a proven resource by c. 1988. A 'retro'-checked power potential estimate of the field

with its characteristics as known at that time indicated a potential Pe of c. 255 MWe (195 MWe at p = 0.05 and 340 MWe at p=0.95) prior to plant developments. These estimates are almost the same as those for the Kamojang field. Development of the Darajat field, however, was slow and started with the installation of a 55 MWe plant in 1994. The total running capacity increased to c. 150 MWe in 2000 and to c. 260 MWe in 2008.

Power potential estimates have not been published for the Awibengkok (Salak) field (all estimates were kept confidential). However, the approximate target likely reservoir area was already known by 1977/1981. The results of the first deep flow-tested wells in 1985 established this prospect as a proven resource. A retro Pe estimate of the field using its 1985 status (see Appendix I) indicates a Pe value of c. 355 MWe (235 MWe at p = 0.05 and 505 MWe at p = 0.95). The first plant with a 110 MWe capacity was installed in 1994. The next plants erected in 1997 followed a rather aggressive development policy which increased plant capacity by 220 MWe. A small topping-up plant with a capacity of 47 MWe lifted the total plant capacity to 377 MWe in 2002, this is still its present running capacity.

The Wayang Windu field had already been explored by 1991 when a potential Pe of c. 185 MWe was indicated for a reservoir which contains a thick vapour layer which is supplied by vapour from a deep coherent brine layer close to boiling. Further exploration and drilling indicated a large resource whose N sector could be readily exploited. The Pe estimate for the northern sector when using all known reservoir characteristics points to a potential of c. 230 MWe (within the integrated probability bounds of c. 185 MWe and 285 MWe at p = 0.05 and p = 0.95 respectively). We estimated the potential of the southern part to be c. 70 MWe. The first power plant with a capacity of 110 MWe was commissioned in 1999. The total capacity was increased by a second plant to 225 MWe in 2009, close to its present running capacity.

The likely potential of the Lahendong field (in Sulawesi) can now be estimated with some confidence. Although the field has been explored since the early 1980's and deep flow-tested wells had shown by 1986 that this prospect is a proven resource, a representative cross-sectional area of the reservoir is only known since 2000. Using the 2000 exploration data, a potential of Pe of c. 255 MWe is indicated for the proven resource (within the bounds of 160 MWe and 370 MWe for p = 0.05 and 0.95 respectively). The first plant of 20 MWe was commissioned in 2002, the capacity was increased by additional 20 MWe plants in 2008 and 2009. The present day running capacity is 60 MWe. It is still an under-developed field.

The Dieng field was explored from 1970 onwards. It is a complex volcanic geothermal system. By 1991 three separate reservoirs had been found namely: a volcanic geothermal system (Sikidang field) which contains traces of magmatic fluids, a deep liquid dominated system with neutral pH fluids and very high, deep temperatures (Sileri field), and a system with rather moderate temperatures (the Pakuwaju prospect). The corrosive fluids in the Sikidang field damaged casings and stopped further development after 1998. Late exploration of the Sileri field led to its development from 1995 to 1998. The productivity of this field is confined to a deep layer between 2 and 2.5 km depth. Using the reservoir and test data as known in 2002, a mean power potential of 65 MWe is indicated for this field (within bounds of 40 MWe and 90 MWe at the p = 0.05 and p = 0.95 level respectively). A 60 MWe plant was finally commissioned in 2002. Restricted steam supply has limited the net output ever since. A 'brown-field' estimate of 400 MWe has been quoted in 2010 for the Dieng Field by the Geological Agency of the Ministry of Energy and Mineral Resource (2010).

A geothermal reservoir with traces of magmatic fluids was also encountered at Sibayak (Sumatra). The first flow tested wells proved this to be a small viable resource whose reservoir area and access is restricted. Using exploration and drilling results as published in 1999, a power potential Pe of 25 MWe is indicated for this field. Reservoir modelling of the partially exploited field pointed to a potential of 30 MWe in 2000 (Atmoyo et al., 2001). A 2 MWe pilot plant started production in 1995; the total plant capacity slowly increased to 12 MWe in 2009, its present running capacity. A 'brown-field' Pe estimate of c. 100 MWe is listed in the inventory of the Geological Agency (2010).

5. IMPLICATIONS OF Pe PREDICTIONS FOR INDONESIAN FIELDS

Estimates of the power potential of a 'proven geothermal resource' should also include an assessment whether "the stored energy can be extracted at a cost competitive with other commercial energy sources at the time of their assessment". This rider was included in the first definition of the term: "proven geothermal reserves" as proposed by Muffler (1979). To complete our assessment of the power potential of developed Indonesian fields, we computed the 'levelized costs of electricity (LCoE)' for all seven Indonesian fields. The data were obtained using the historic Pe values discussed in the previous chapter, field characteristics, technology cost and performance data and market demand information (other input parameters are listed for an example in Appendix II). The LCoE costs were also computed using the Monte Carlo simulation procedure and have been plotted versus historic Pe values in Figure 3. The shaded band in the figure indicates a data field which includes the LCoE costs of 12 other Indonesian 'proven geothermal resources' now under development (for confidentiality reasons not presented here).

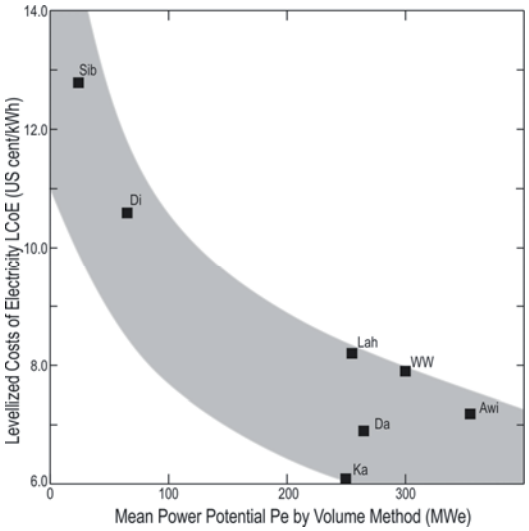


Figure 3: Mean predicted power potential of producing Indonesian fields versus inferred mean levelized cost of electricity for 2010

The sparse data in Figure 3 indicate that the LCoE costs tend to increase significantly for smaller plants. The costs vary also significantly for fields within the Pe range of 250 MWe to 350 MWe. The variations in costs are affected by reservoir characteristics. Costs for fields producing from vapour-dominated reservoirs (Kamojang, Darajat) are lower than those producing from liquid-dominated reservoirs (Lahendong and Awibengkok). With reference to competitive costs, the LCoE costs of plants exploiting reservoirs associated with volcanic geothermal systems (Dieng, Sibayak) appear to be above those of 9.7 US cent/kWh presently adopted by the Government of Indonesia as a ceiling below which PLN, the Indonesian national utility, is obligated to purchase the power.

6. SUMMARY

Electric power potential estimates (Pe values) have been used over the last three decades in the development of 16 presently producing geothermal fields in the Philippines and Indonesia (with a combined total running capacity of c. 2,500 MWe). Some of the early Pe estimates were published. We computed 'historic Pe estimates' for other fields using exploration and well test data available at the time when decisions about plant development were made. All historic Pe estimates were made using the volume-stored heat method. Most of the estimates yielded rather conservative Pe values by using, for example, conservative estimates for the so-called recovery factor. Reservoir modelling showed later that recovery of useable energy can increase with natural recharge and proper reservoir (exploitation) management. Most of the earlier Pe estimates at proven reserve status produced realistic long-term, order of magnitude power potentials. The present day running capacity of fields under exploitation is approaching these estimates which often have been upgraded by later simulation and modelling studies.

Nonetheless, while Pe calculations generally provide reliable guidance on the order of magnitude of potential power output, care must be taken applying the method in particular circumstances. The likely type of geothermal system was not recognised in most of the early assessments. Pe over-estimates of the likely potential of the Palinpinon and Tiwi fields in the Philippines can now be seen as a failure of not recognising the importance of concealed outflow structures of these prospects towards the end of the main exploration phase. The problem of obtaining a representative Pe estimate for volcanic geothermal systems in Indonesia can be understood with reference to the exploited Dieng and the Sibayak fields. Even recent brown-field Pe predictions of these two prospects indicate over-estimates which do not recognize the restrictions of systems which are difficult to develop and are associated with rather high levelized LCoE costs.

After c. 30 years of using the simple volume-stored heat method to predict the Pe of fields considered for development, we are only a bit further than in 1982 when a study by Watson and Maunder (1982) closed with the quote: "Stored heat calculations are very simple in concept. Any attempt to 'polish' them leads to the same difficulties faced by modelling or simulation techniques."

Appendix I

Example of an early Pe estimate of a geothermal field using the stored heat (volume) method

An example of the simple model used to estimate the power potential Pe of a prospect of proven reserve status is shown below. A version of the stored heat method had already been used for the assessment of Pe values of Philippine geothermal fields (Watson and Maunder, 1982). We used a slightly revised algorithm similar to that of Sarmiento and Steingrimsson (2008) and their addition of a Monte Carlo simulation to assess the effect of uncertainties of input parameters.

A simple 'box-type' model of the Awibengkok Field as known in 1985 is shown in Figure 4. The cross-sectional area A was inferred to be c. 37 km2 as indicated by earlier resistivity surveys recently documented by Hochstein and Sudarman (2009). The deep, flow-tested AW-2 well in 1985 provided important information about the temperature structure and fluid characteristics. The model allows a conservative estimate of the likely power potential of the field since useable heat stored in rocks above sea level and below - 1.5 km depth level was not considered. A conservative mean estimate of r = 0.2 was also used for the useable energy recovery factor.

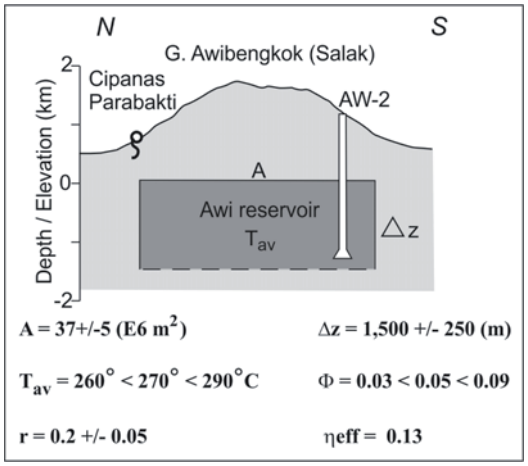


Figure 4: Box model of the Awibengkok field (1985 status) used for an early Pe estimate with the stored heat (volume) method

With a mean conversion efficiency of 0.13 and an inferred plant life of 30 yr, a mean Pe value of 355 MW/yr was obtained which lies within the integrated probability bounds of p = 0.05 (235 MWe) and p = 0.95 (505 Mwe) indicating low and high risk predictions respectively.
Later actual developments showed that the inferred cross-sectional area of the productive reservoir had been over-estimated. For the developed field it is now c. 30 km2 (Stimac et al., 2008). The adopted re-injection management strategy has also increased significantly energy recovery. However, the early Pe estimate of the Awibengkok field at the undeveloped stage remains as a benchmark for subsequent developments.

Appendix II

Computing levelized costs of electric power (LCoE) of Indonesian proven high T fields

LCoE costs were estimated at proven reserve status using geothermal field characteristics data, Pe data, cost data and market demand information. If average reservoir temperature T av was > 210 deg C, flash plant technology was adopted. LCoE costs were computed in terms of 2010 constant currency units such that the present value (PV) of revenues equals the life-cycle costs over investment/ development period and a 30 yr operating period.

Discount rate was based on weighted costs of capital (WACC) defined in probability terms reflecting: range of possible capital structure, risk premia, and risk-free interest rates (mean value of 10.2% 'real'). The Monte Carlo simulation was used which yields the probability distribution for the present value (PV) of total project capital and operating costs. The LCoE values obtained refer to a cumulative probability of p = 0.5 in the probability distribution.

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