**Geothermal life-cycle model (version 1, 20 Feb. 2017)**

1. **General description of the model**

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| **Purpose of the model**: The model is a *full-field,* Technical-to-Business XL-model consisting of coupled volumetric (Heat-In-Place), production, and cashflow parts. Output consists of a range of Key Performance Indicators (KPIs) and of various graphs of time-series etc. When combined with a Monte Carlo engine such as Crystal Ball or @Risk, the XL-model can compute stochastic time-series and histograms of KPIs. A particularly useful feature is the sensitivity analysis that can be done using Monte Carlo sampling. The model is targeted at geothermal assets (projects) that are relatively immature, i.e. assets with relatively large uncertainties for the non-controllable variables, and with a wide range of possible project definitions (controllable variables). Typically, such geothermal fields, or geothermal development projects, would be in the "pre-feasibility" or "concept selection" phase. Results from studies done with this XL model may be used to narrow down (i.e. further frame) the possible project definitions to be elaborated in subsequent steps (feasibility study, concept selection, FEED). In such further studies, more detailed models would be typically used. |
| The model consists of a volumetric part, which computes the **Heat-In-Place** and the theoretically maximum possible electrical power capacity from this Heat-In-Place, based on a given economic life-time and some empirical correlations. The (volcanic) reservoir is assumed to be non-depletable over the asset's life-cycle, both in terms of fluid/mass-in-place and in terms of heat-in-place. Produced fluid is assumed to be replenished by injected fluid and/or natural water influx (meteoric water, other groundwater), heat is assumed to be unlimited in production terms, as over 90% of the Heat-In-Place is assumed to be in the solid minerals of the rock, which would re-supply the heat to the re-injected cooled-down fluids in the pores at an, in practical terms, unlimited rate. Also, it is assumed that in practical terms Heat-In-Place and mass/heat production is hardly influenced by whether the reservoir fluids consist of steam+water, or just water. Existing studies argue that this difference can be assumed to be negligible. Based on the **steady-state well inflow equation**, the model then computes the mass and heat production per well. The steady-state inflow equation corrects the drainage area per well for the number of (initial and incremental) wells. The given (initial) skin-factor per well influences the well's productivity. A user-defined skin build-up rate (factor/year) results in the well's productivity to decline over the years, until a skin-removal **workover** is scheduled and the skin factor is re-set at the original value. The user can supply the workover frequency. The workover opex will be accrued to the cash-out cashflow. |
| **Wells** with individual, heterogeneous properties and separate field-sectors (e.g. fault-blocks) cannot be modelled. All wells are assumed to be identical, and the reservoir is just one body with a constant reservoir-boundary pressure that does not deplete in time. For input variables that are heterogeneous in space and/or changing in time, it is assumed that they can be adequately represented by field-wide average values. This assumption is a coarse simplification and should in principle be verified by calibration to more detailed models. But as a first approximation it may well be a valid assumption. All yearly average **production** is corrected for a given load time (uptime) factor, or for the given number of running hours per year. Total field production is the sum of all individual well production rates, unless constrained by surface facilities. A targeted plateau production can be given: the model will automatically drill additional wells if the target is not being met (e.g. due to well deterioration, or if the target rate is increased in a given year). The number of production wells to be drilled each year is then used to calculate the yearly drilling expenditure (drillex) and, hence, depreciation, tax and NCF. The user can supply a producer to injector ratio. When specifying / computing a new production well, the corresponding number of injectors will be automatically and accrued to the drillex, and later to the well-opex (e.g. for the number of workovers to be done). |
| **Lifting costs** are computed from a well's pump specifications (power-rating), or from the physical equations for the work required to lift a certain volume of water. The required electrical power is deducted from the total electrical power production to compute **electricity sales**. |
| **Capex** can be specified per project phase, ie. exploration, appraisal, early development and incremental development. Capex uncertainty can be specified using a capex-multiplier. Similarly, the **drillex** uncertainty. |
| The **fixed opex** and O&M costs are input by the user as a time-series. Based on the user-specified input, the **variable opex** is automatically calculated for the following components: **water opex** (function of water rate); **well opex** (function of total number of production + injection wells in operation); and **well workovers** (function of cost per workover and workover frequency per well). |
| **Surface facilities** are implicitly modelled by allowing for a range of capex entries and by enabling alternative calculation methods to compute the **conversion efficiency** of the field's mass/heat production to electrical power. This version therefore does not allow for a detailed breakdown of the computed performance (physics, cash) per facility item. |
| Nor does this version allow for the calculation of the **CO2 footprint**. This is planned for a later version. |
| In this version, no facility exists to include **inflation** / cost escalators to compute MOD (Money-of-the-Day). See also comments below under "Some notes on Decision-making & Valuation" / "Some opinions on the nominal dollars vs. real terms dollars dilemma". For the time being, no other currencies / exchange rates are enabled. |
| The **tax regime** is a contractor / concession agreement with *royalty* and *corporate tax*. The project is assumed to be *ringfenced*. Royalty payments are optionally tax deductible. To calculate the fiscal income, capex is depreciated according to either a *straight line depreciation, declining balance depreciation, or double declining balance depreciation scheme*. The number of depreciation years and salvage value are to be specified by the user. The depreciation schedule starts in the the year that the capital was spent. Specific conditions for the **Indonesian geothermal market** (Geothermal law etc.) have not been modelled in detail. |
| **Decommissioning:** the field is abandoned based on a user-supplied integer number of consecutive years during which the (undiscounted) net cash flow (NCF) is negative. Following a user-defined mandatory monitoring period to ascertain well integrity and other environmental conditions, abandonment capex is then accrued to the cashflow. Abandoment capex can be specified either as a percentage of cumulative capex, or as a fixed number. For the time being there is no tax provision for this abandonment capex (Loss Carry Back: i.e. correct taxable income well before the year of abandonment, in years during which a profit is still being made). |
| Model outputcan be inspected as **KPIs** and **performance graphs** in the pertinent worksheets. When linked to a MonteCarlo engine, **probabilistic time-series** and **KPI-histograms** can also be inspected. Probabilistic **sensitivity analysis** can then be performed. The sales-tariff to Indonesian state monopolist PLN can for example be computed and matched to an IRR hurdle rate. |

1. **Model input**

Below follow some screenshots for the tool’s **input** variables.

**Scalar input variables:**







**Time-series** **input variables:**



**Stochastic input variables:**

When linked to Crystal Ball, the non-controllable uncertain input variables can be defined stochastically. Examples are: porosity, permeability, skin build-up rate, well drilling cost, well stimulation cost, well workover cost, etc.

Crystal Ball allows such variables to be defined through pdf’s (probability density functions), and allow such variable to be correlated stochastically, i.e. using a correlation coefficient. The shape of the pdf and the correlation coefficients determine the Monte Carlo sampling process and, hence, the computation of the output KPI-histograms and probabilistic time-series. Reference is made to the Crystal Ball XL plug-in.

1. **Examples of model output**

Below follow some screenshots for the tool’s **output** variables.



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When processing the XL model together with the statistical XL plug-in **Crystal Ball**, the following type of output can also be obtained (note that the graphs below come from an oilfield application, but similar stochastic output will be obtained from the geothermal tool):

**Histograms of KPIs**

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**Probabilistic time-series and other probabilistic output**

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**Sensitivity analyses**

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