Using Decision support models for EGS performance optimisation

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WP9 Leiden Workshop, november 2007:
D. Bruhn, E. Huenges, C. Karytsas, T. Kohl, P. Ledru, E. Simmelink and other participants

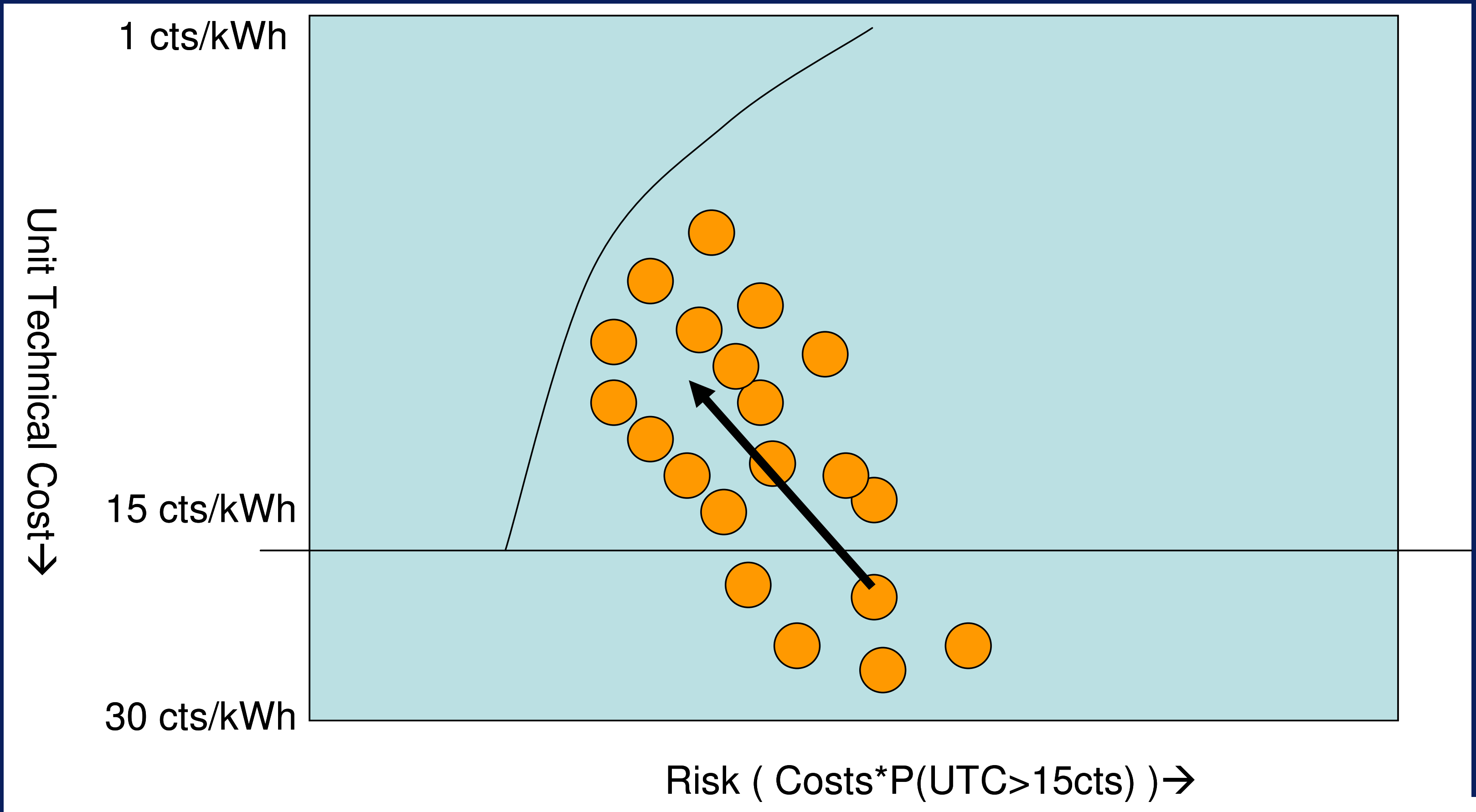
Leiden Workshop: three aspects to performance

- **Make the project fly economically → techno-economic assessment → EXCEL**

- **Constraints for the project by government (e.g. induced earthquakes within limits → HAZOP, contingency plans)**
- **Legislation and PR bottlenecks (delaying $t_{\text{first electricity}}$)**

Leiden workshop, november 2007

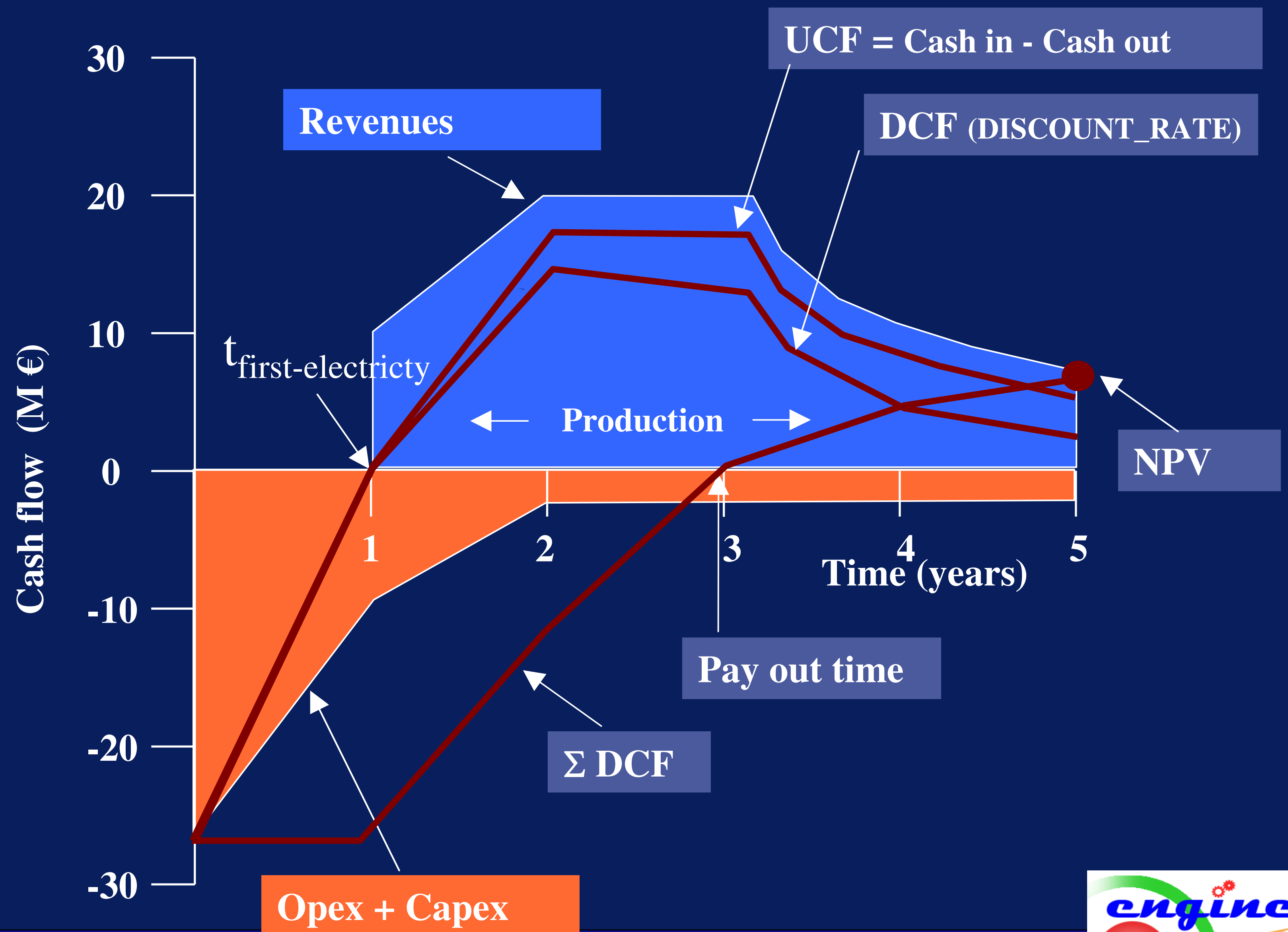
AIM of future research →
bring UTC below 15cts/kWh



Contents

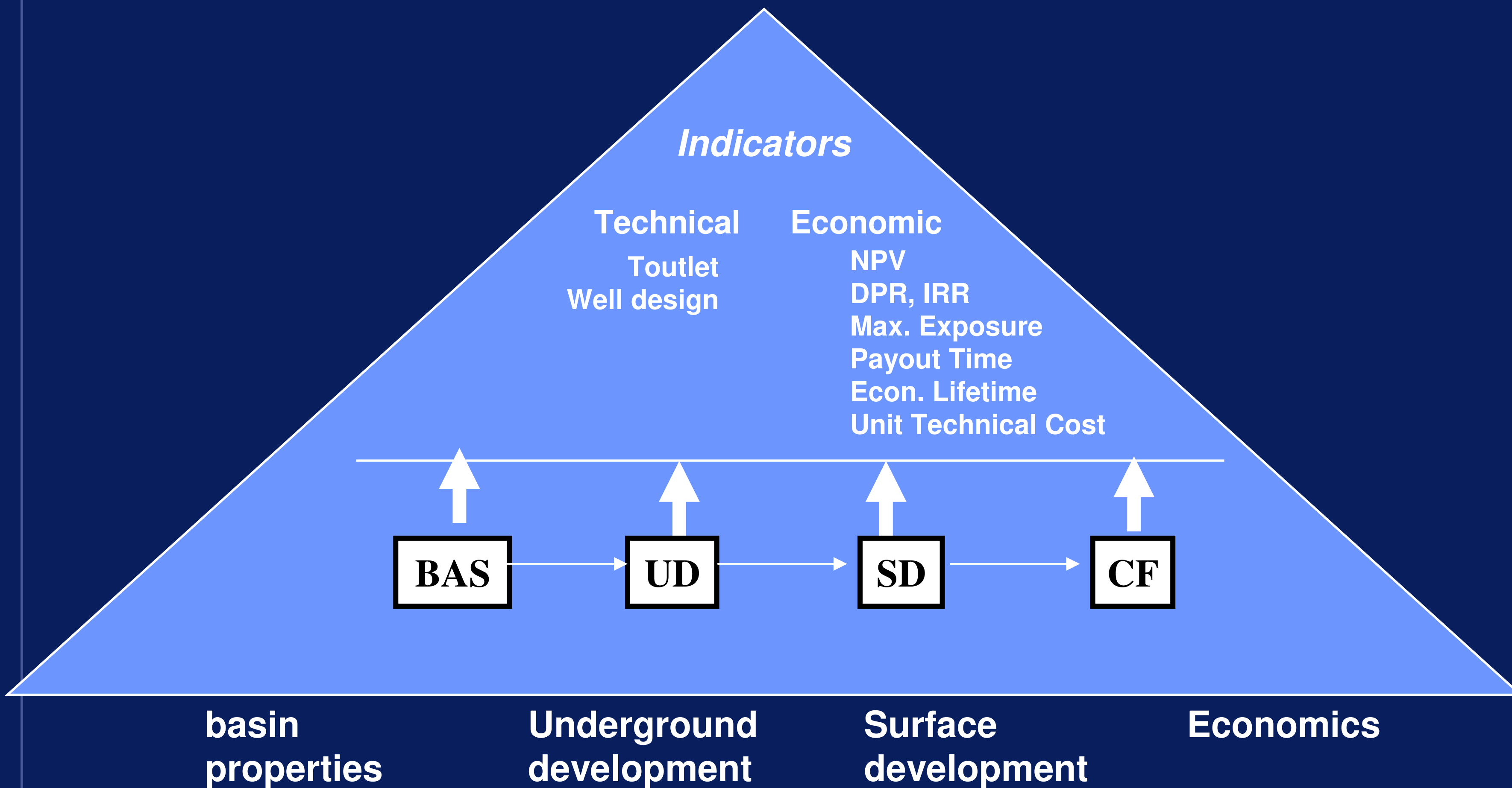
- **Performance calculation -EXCEL**
- **Taking into account uncertainties and engineering options**
  - Best practices Asset development decisions E&P
  - Decision support system
- **Applications to EGS**

CO- CashFlow



UCF = Cash in - Cash out
Revenues
DCF (DISCOUNT_RATE)
30
20
10
0
-10
-20
-30
Cash flow (M €)
$t_{first-electricty}$
Production
NPV
1
2
3
4
5
Time (years)
Pay out time
Σ DCF
Opex + Capex

Techno-ecomonic calculation→ Fast computational models



driving philosophy is to trade-off accuracy for completeness

FAST ANALYTICAL MODEL for EGS, EXCEL

Microsoft Excel - egs_v7_dss_soultz.xls

psimax =-0.5*Mplot

Yearly Temperatures --> electricity production

To do

control 3.7 0

Geological Parameters

Thermal gradient (°C/m)	grad_TG	0.038
Temperature of the reservoir (°C)	TG	200
Annual mean surface temperature (°C	Tsurf	10
Diffusivity of the rocks (m²/s)	kapg	1.11E-06
Conductivity of the rocks (W/(m.K))	kg	3
Specific heat of the rocks (J/(kg.K))	cg	1000
Density of the rocks (Kg/m3)	rg	2700
density of fluid (Kf/m3)	rf	1065
Specific heat of the fluid (J/(kg.K))	cf	4250
G-force (m/s)	g	9.81

Production variables

number of fitted pumps	numberpur	2
T0 [C]	T0	20
Th [C]		165
Tc[C]	Tc	60
curnot Max triangular		0.198358
curnot relative efficiency	curnotrelat	0.68

Legend CB = Crystal Ball

- Input variable (deterministic)
- Input: possible stoch. input var.
- Input: stoch. input variable (CB)
- Input: decision (CB)
- Output: calculated result
- Special, see comment

fixed input values
Input values
Calculate values

Engeneering Parameters

conversion time in yrs -> time in seconds	tyts	31536000
Borehole parameters		
Borehole length (m)	zg	5000
Borehole diameter (m)	dB	0.1778
Roughness of the pipes (mm)	ks	0
Relative roughness of the pipes =ks/dB	rks	0
Fluid / Circulation parameters		
Critical Reynold number	Rec	2300
Temperature inlet at the injection well (°C)	Tin	60
Flow rate (Kg/s)	Q	50
Flow rate for one streamline sector - Qs=Q/12 (kg/s)	Qs	4.16666667
Pressure parameters		
Apparent injectivity indices (l/s/Mpa)	II	3.5
Apparent productivity indices (l/s/Mpa)	PI	7.2
P. require for the inj. borehole at the res. (Mpa)	PIr	14.2857143
P. require for the prod. borehole at the res. (Mpa)	PPr	6.944
Reservoir parameters		
Distance between the two boreholes (Km)	Dist	0.7
Half distance well (Km)	aplot	0.35
Total Area fracture (Km²)	AreaF	3
Radius of the fracture (Km)	r	0.977
Square of the radius	r^2	0.955
Number of fracture in the reservoir	Num	4
Aperture of the fracture (mm)	w	2
Enery parameters		
energy consumption of the pump (kWe/Mpa)	Epump	50
Streamline parameters		
	iterdif	3.00E-03
at 0,ttiny	psimax	-4.16E+00
number of streamlines	segments	6
	Uplot	1

% from fracture	30.00%

Phasing variables

First year of evaluation	2007
First year of production	2009
year of Injector well	2007
year of production well	2007
year of plant construction	2007
duration of plant construction	2
pump replacement [yrs]	4

Economic variables

electricity Price to sell [cts/kWh]	15
electricity Cost to buy [cts/kWh]	15
Royalty (% of electricity sales)	0
Is royalty tax deductible Y/N?	Y
Tax (% taxable income)	40
Depreciation (SLCA: nr years)	10
Uplift (#yrs from taxable income>0)	1
Capex multiplier	1.00
Fixed opex multiplier	1.00
discount rate	6.00%
Economic field prod limit (Mwe)	2

costs

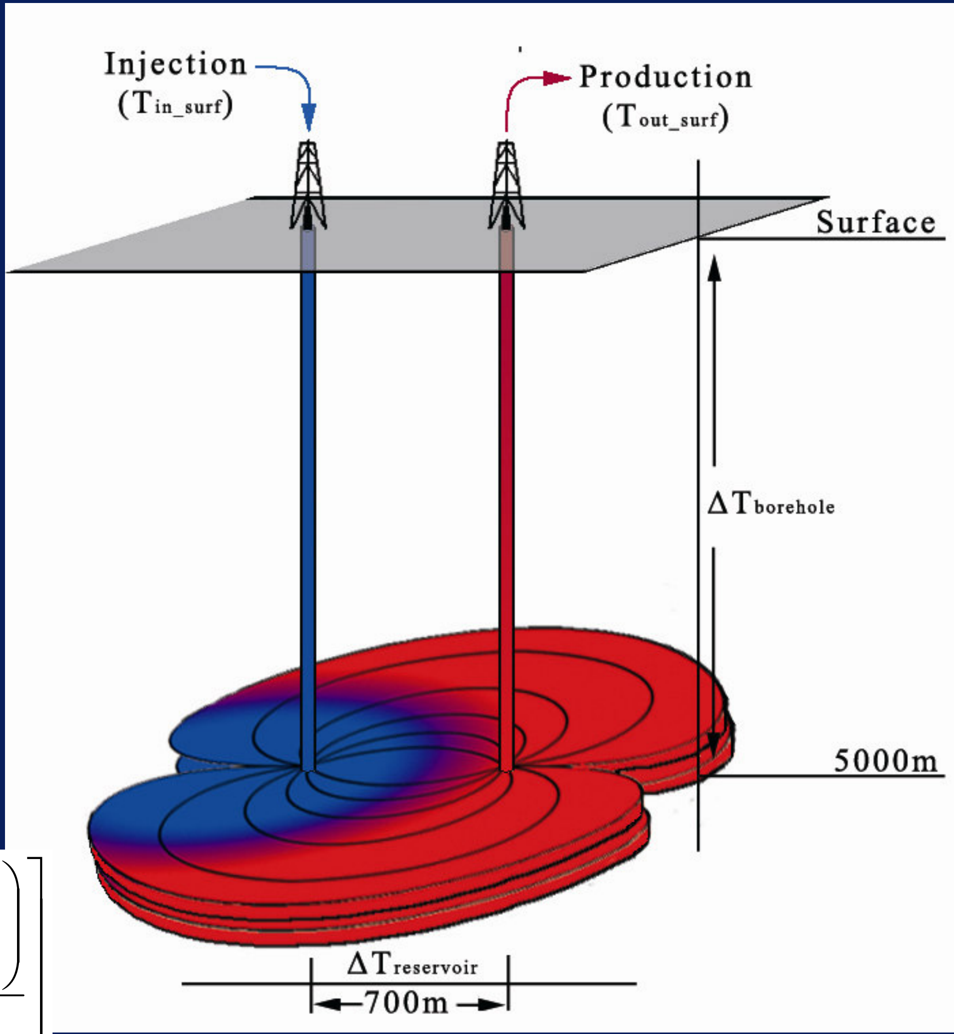
single well cost [mln €]	6.00
stimulations costs [mln	0.55
plant cost [mln €/MWe]	1.5
installed capacity	5
plant cost [mln]	7.50
running hours/yr	8000
injection/production pump [mln €]	1.375
pump workover costs	1
pump power [kWe/Mpa]	50.00
fixed opex	5.00%
plant electricity consumption [%]	5.00%

Intro / Cashflow / KPIs / fig undisc CF / CumCF / fig CumCF / DCF / fig DCF / CumDCF / fig CumDCF / temperature / Thermal_solutions / area_solution / streamlinesplot / fig Prod / fig Opex / Spider

Brief explanation of rationale behind these models

Streamline approach for fracture flow (Pruess and Bodvarsson, 1983; Heidinger et al., 2006)

Area of fractures (A) and flow rate (Q) and Number of fractures (N) primarily relate to the sustainibility in time of the high temperatures.



$$T_{out\_res} = T_G - (T_G - T_{in\_res})\, erfc\left[\frac{\dfrac{\sqrt{c_G \lambda_G \rho_G}}{c_F} \left(\dfrac{Narea_{Seg}}{(Q_{seg})} \right)}{\sqrt{t - tdel}} \right]$$

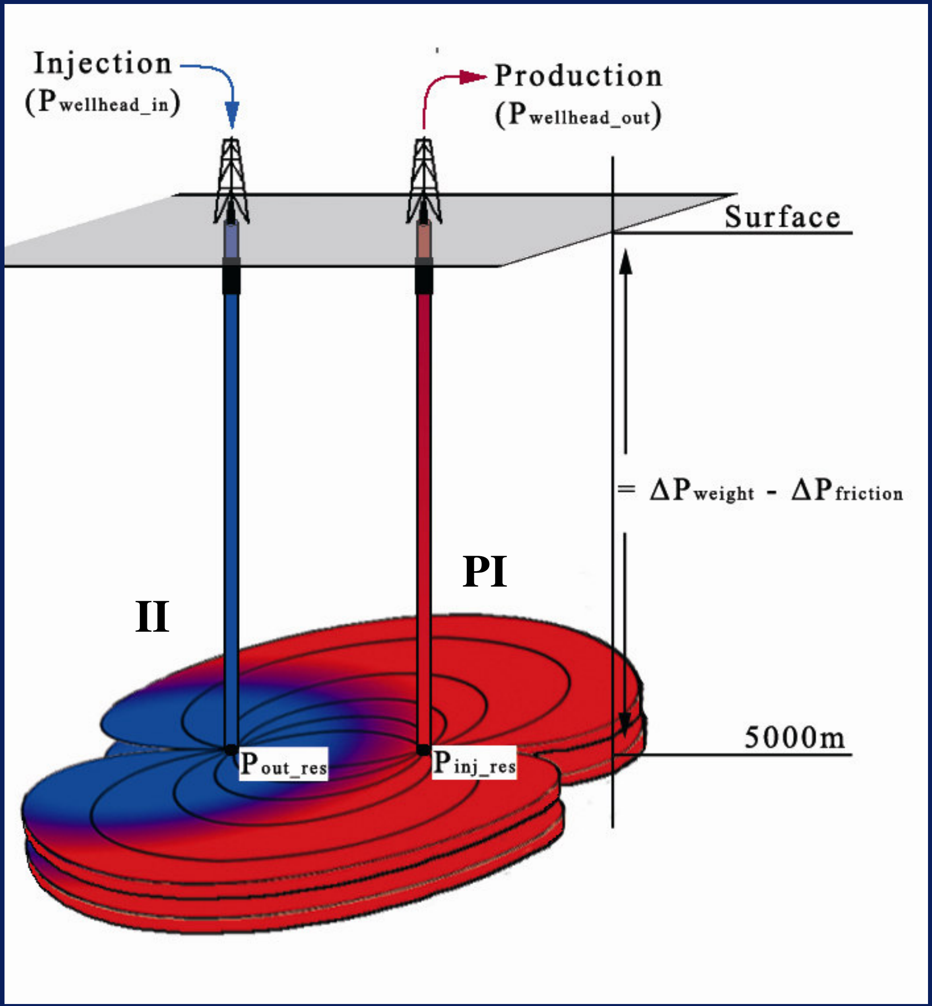
Brief explanation of rationale behind these models

Circulation test :

- II: L/s MPa at res
- PI: l/s MPa at res

Target flowrate→

- injection+production pumps
- friction and thermal expansion



Model based on fracture flow (Pruess and Bodvarsson, 1980; Heidinger et al., 2006)

FAST ANALYTICAL MODEL for EGS, EXCEL

Project Key Performance Indicators

#REF!

Royalty = 0% & tax-deductible; Tax = 40%; Depreciation period = 10 yrs; Uplift = 1 yrs

KPI	Value	Unit	Comment
Technical ultimate geothermal recovery	753.2	GWe	not constrained
ultimate recovery produced economically	753.2	GWe	only constrained by "economic limit"
PV electricity sales	50.2	mln €	
PV Government Take @PV6%, ref 2007	5.0	mln €	
NPV@PV6%, ref 2007	0.2	mln €	
IRR	6.1%		IRR=-100% if NPV<0, result sometimes wrong
Maximum exposure (undiscounted CF)	-22.3	mln €	Max. undiscounted exposure in year 2008
Maximum exposure (discounted CF)	-21.9	mln €	Max. discounted exposure in year 2008
PIR undiscounted	0.55	ratio	
PIR discounted	0.01	ratio	
Unit Technical Cost (undiscounted cost/kWh)	0.10	€/kWh	
Unit Technical Cost (Pvcost/kWh)	0.06	€/kWh	
Unit Technical Cost (PVcost/PVkWh)	0.13	€/kWh	
Pay-out time (undiscounted cashflow)	12	years	
Pay-out time (discounted cashflow)	30	years	
Productive life of asset	>28	years	Still producing at end of evaluation period

Taking into account uncertainties and engineering options

TNOs experience from Oil and Gas E&P "Decision and risk management" Research consortia (1997-2003)

E&P DECISION SUPPORT SYSTEMS

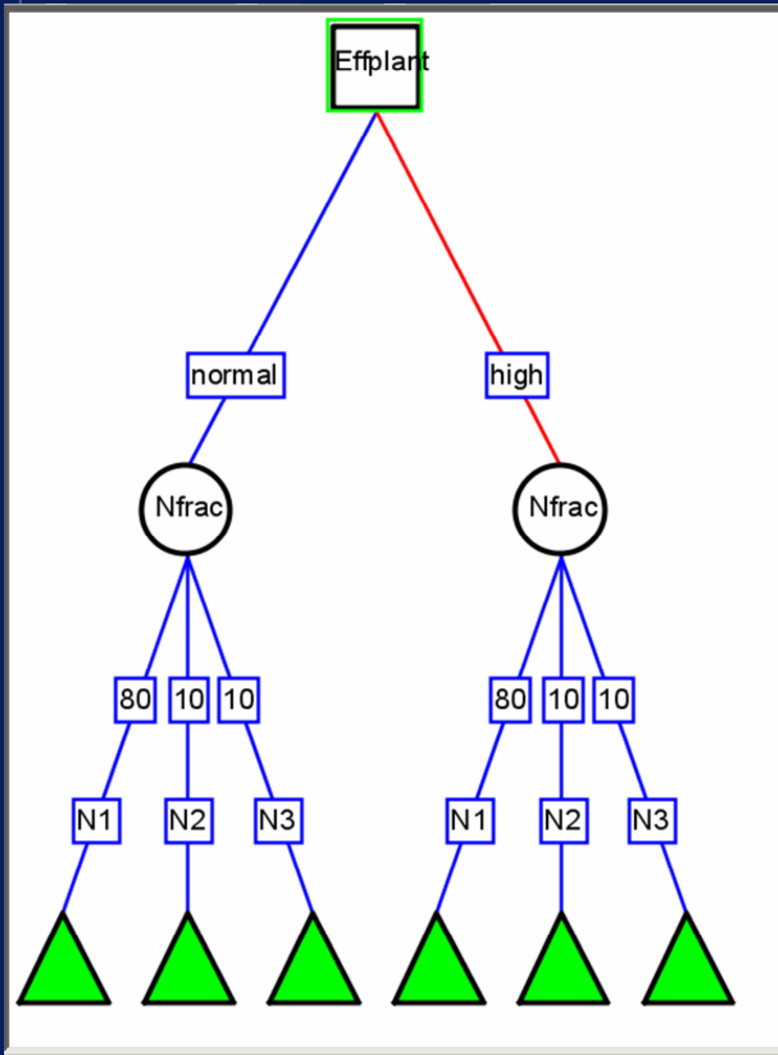
Anadarko Petroleum Corporation

BHPBilliton

- Scenarios **AND** Continuous probability functions (MC)

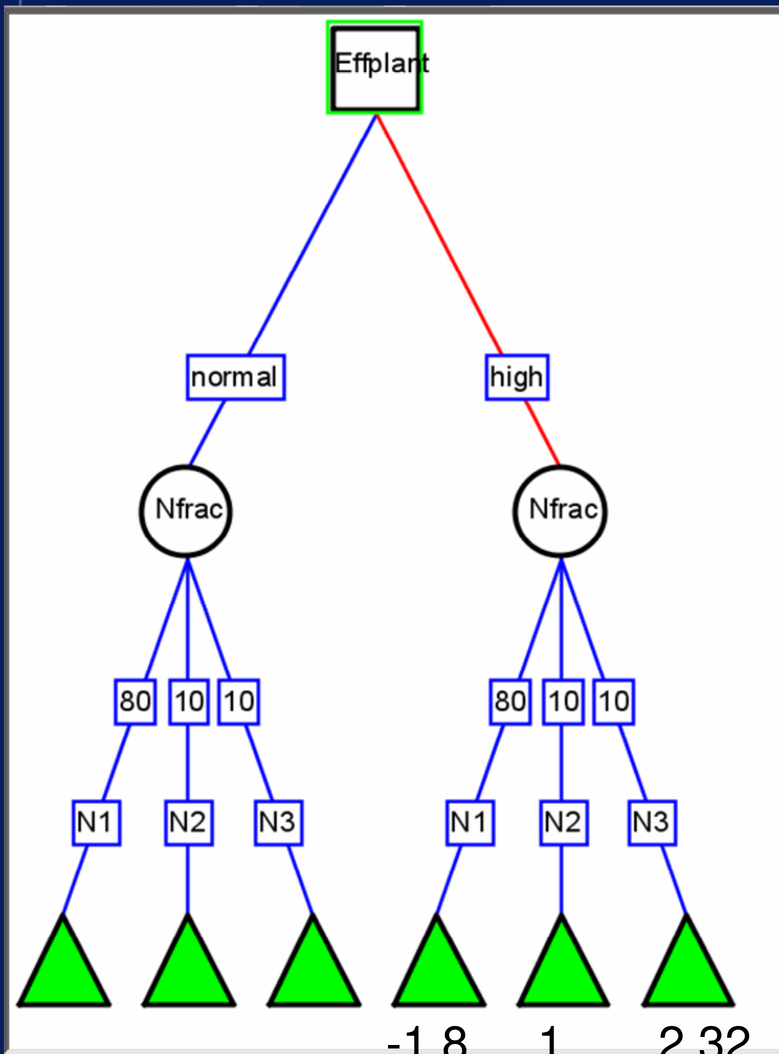
DSS model : Mixing discrete and continuous uncertainties, decision trees

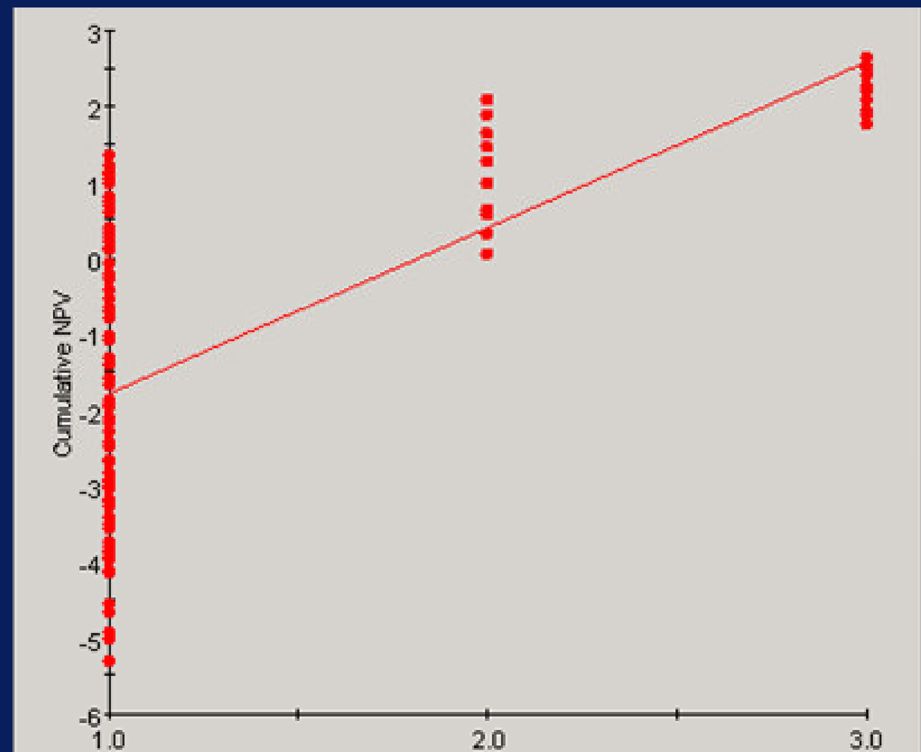
- **Design decision (discrete)**
  - Normal plant (costs 1.5 mln/ MWe, eff=0.68)
  - Higheff plant (costs 2 mln/ MWe, eff=0.8)
- **Uncertainties (continuous)**
  - Fracture area 2-4 km2
  - Inflow other than "connected" fracture 50-90%
- **Uncertainties (discrete)**
  - Having 1 (80%) ,2 or 3 fractures (each 10%)

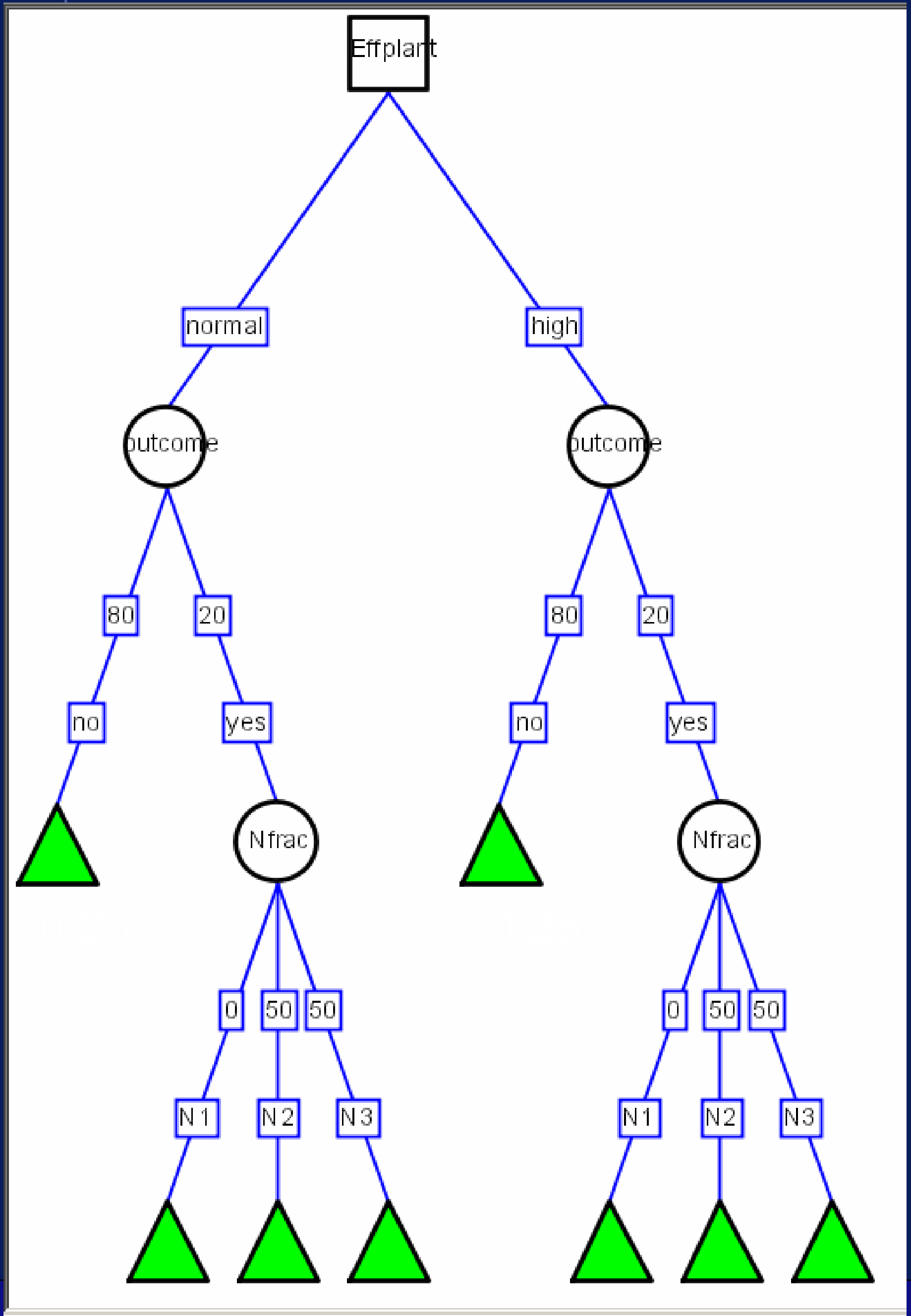

Effplant
normal
high
Nfrac
Nfrac
80
10
10
80
10
10
N1
N2
N3
N1
N2
N3


expectation: Cumulative NPV (+dead end)
expectation
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-6
-5
-4
-3
-2
-1
0
1
2
3

NPV

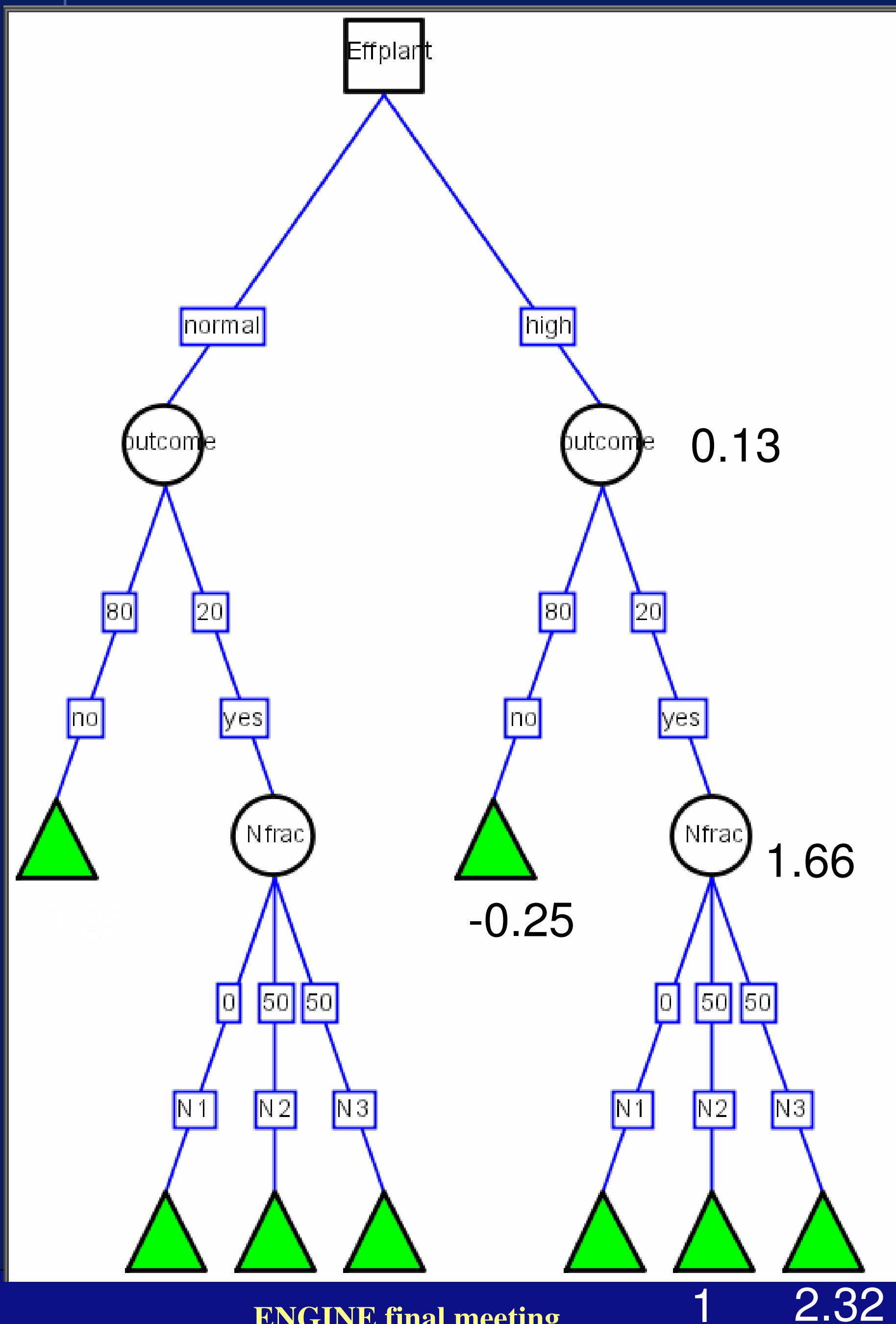

Effplant
normal
high
Nfrac
Nfrac
80
10
10
80
10
10
N1
N2
N3
N1
N2
N3
-1.8
1
2.32

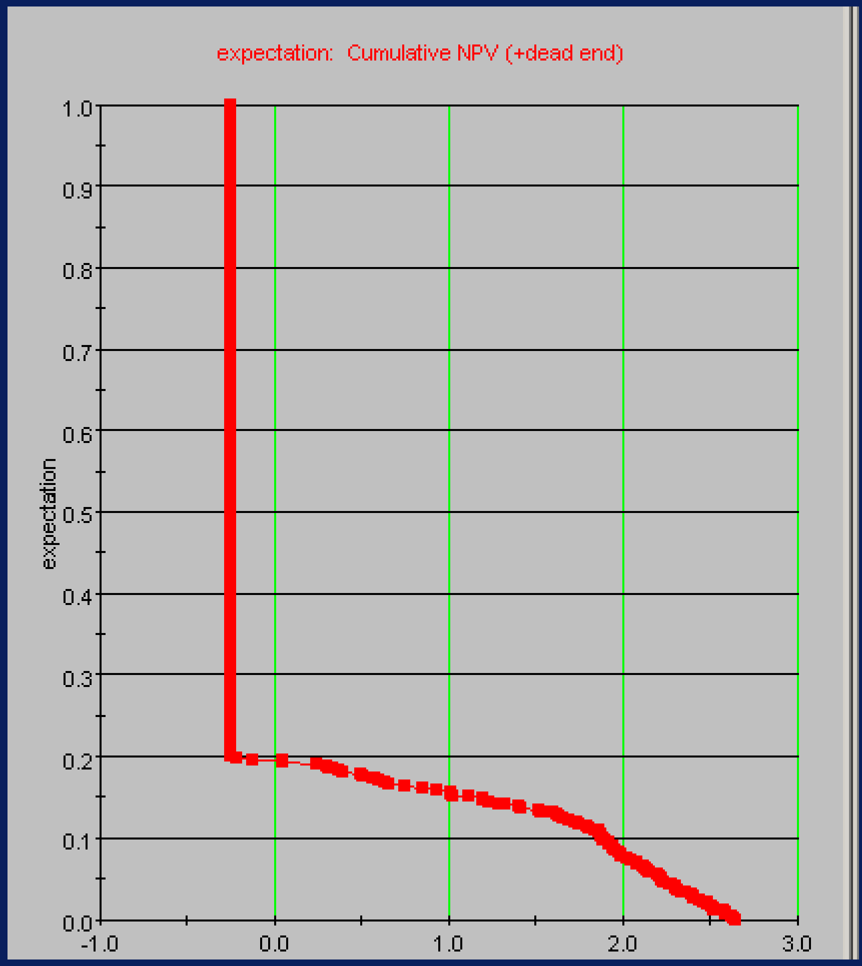

Cumulative NPV
3
2
1
0
-1
-2
-3
-4
-5
-6
1.0
2.0
3.0



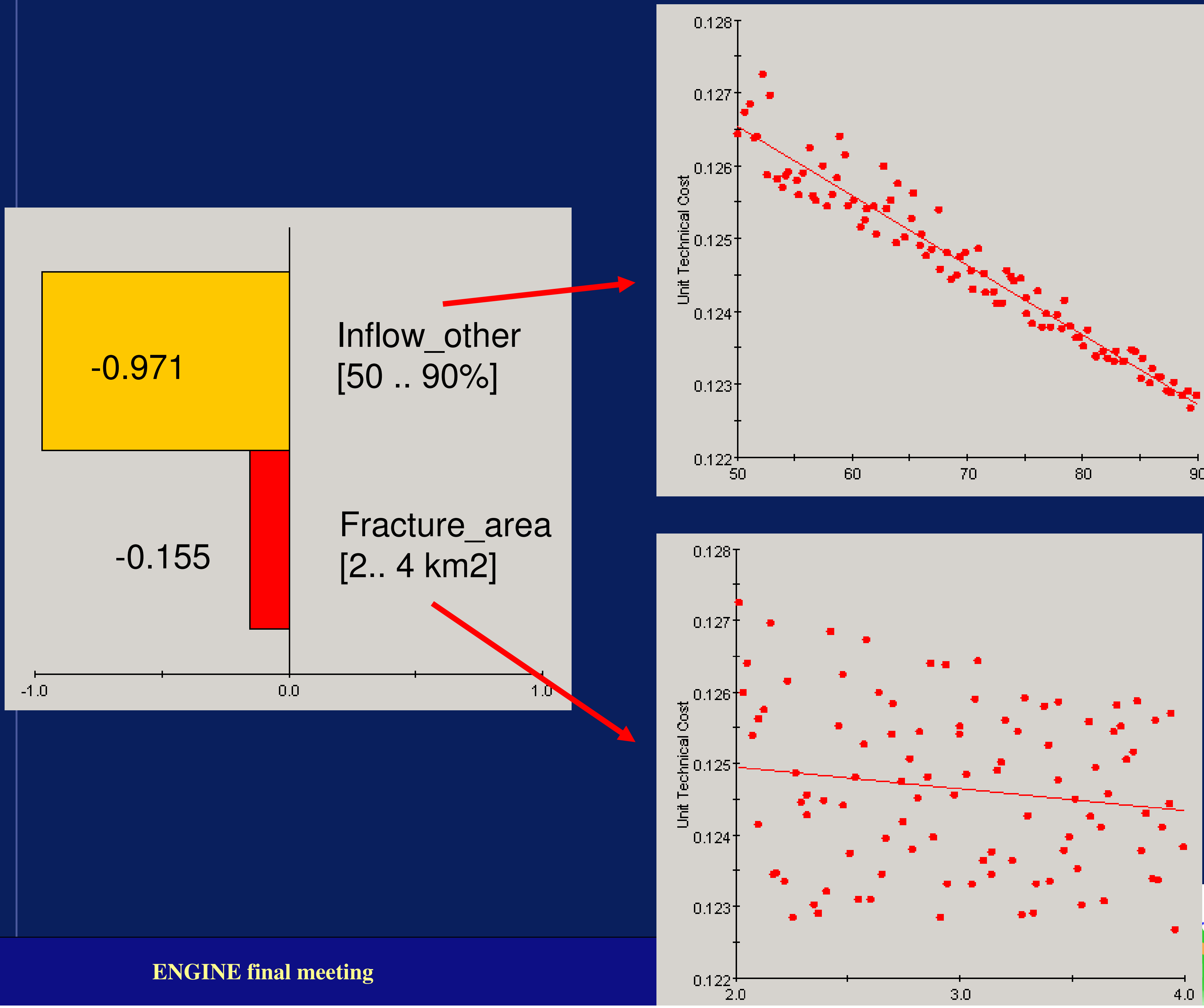
Introducing an information acquisition phase, which allows to rule out N1

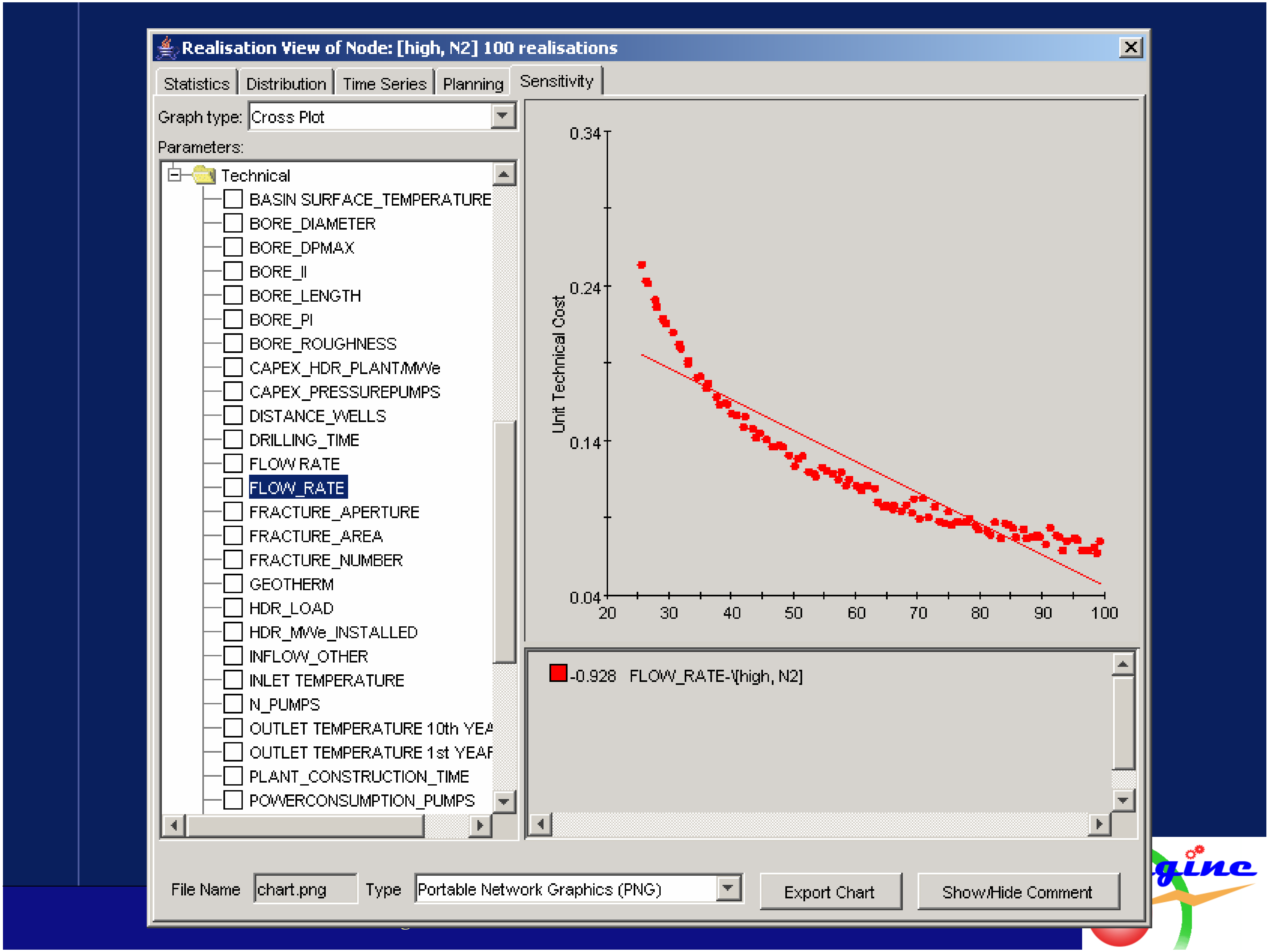
Costs are 250 kEURO

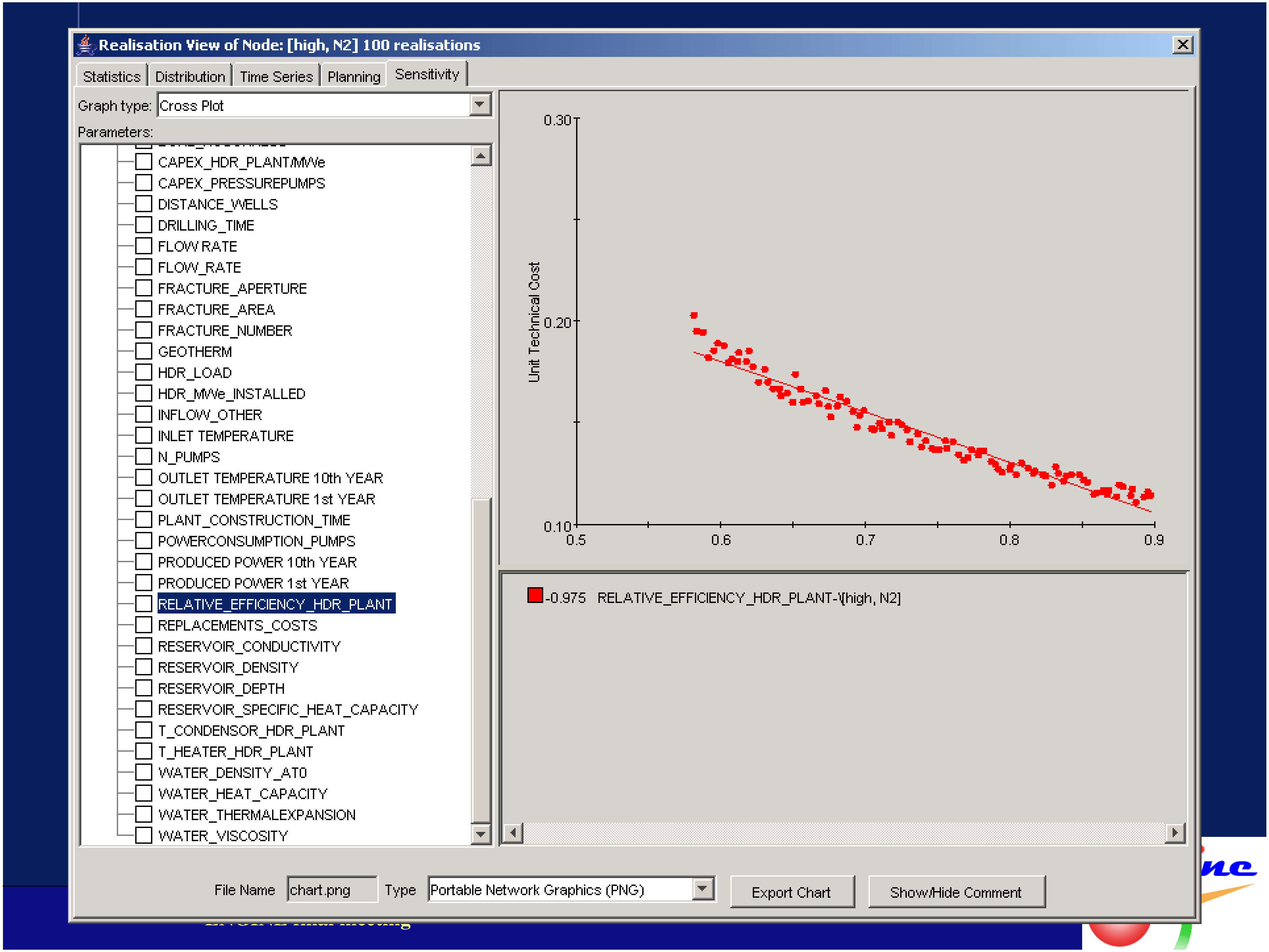

Effplant
normal
high
outcome
outcome
0.13
80
20
80
20
no
yes
no
yes
Nfrac
Nfrac
1.66
-0.25
0
50
50
0
50
50
N1
N2
N3
N1
N2
N3
1
2.32


expectation: Cumulative NPV (+dead end)
expectation
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-1.0
0.0
1.0
2.0
3.0

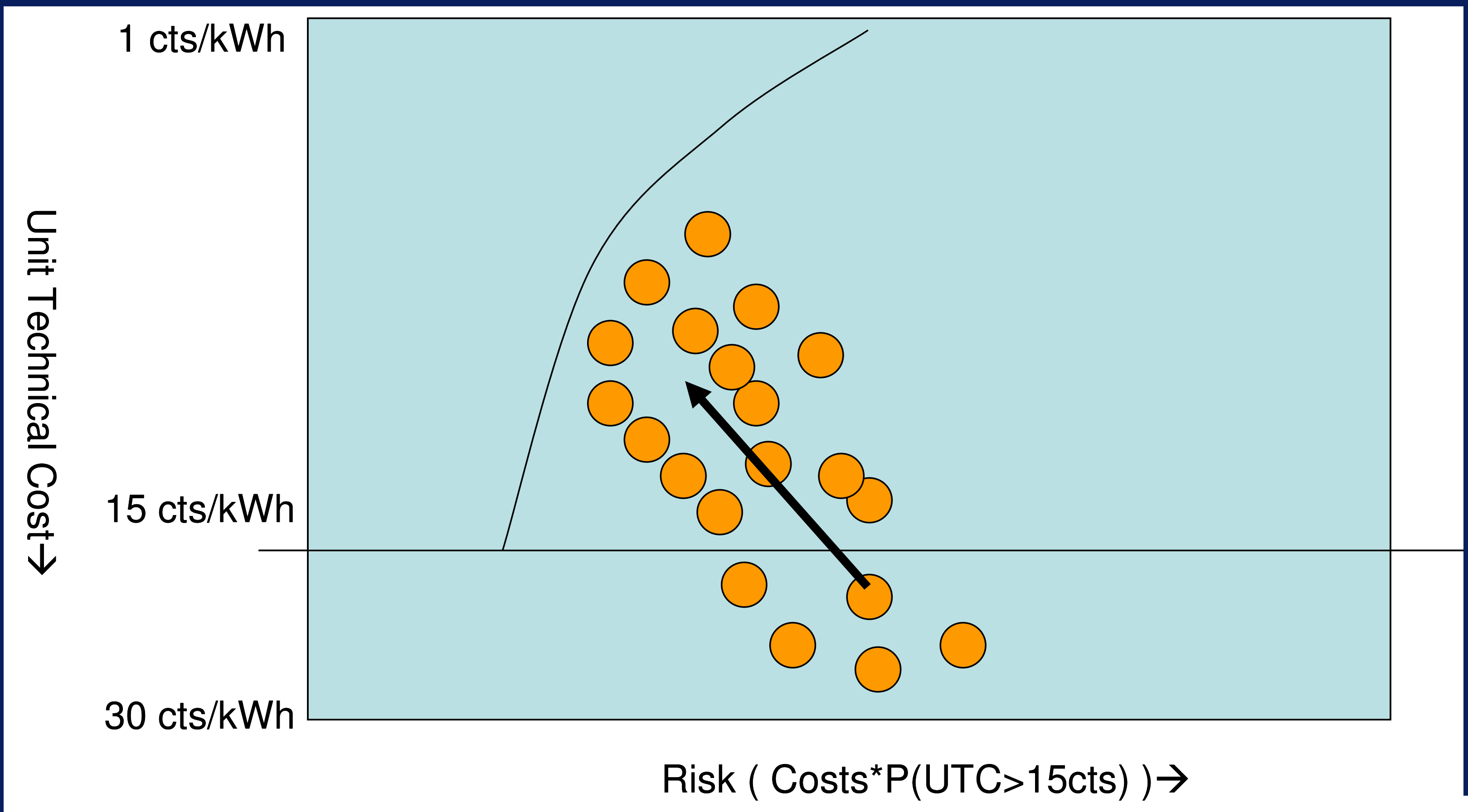
NPV


-0.971
Inflow_other
[50 .. 90%]
-0.155
Fracture_area
[2.. 4 km2]
-1.0
0.0
1.0
Unit Technical Cost
0.128
0.127
0.126
0.125
0.124
0.123
0.122
50
60
70
80
90
Unit Technical Cost
0.128
0.127
0.126
0.125
0.124
0.123
0.122
2.0
3.0
4.0


Realisation View of Node: [high, N2] 100 realisations
Statistics
Distribution
Time Series
Planning
Sensitivity
Graph type:
Cross Plot
Parameters:
Technical
BASIN SURFACE_TEMPERATURE
BORE_DIAMETER
BORE_DPMAX
BORE_II
BORE_LENGTH
BORE_PI
BORE_ROUGHNESS
CAPEX_HDR_PLANT/MWe
CAPEX_PRESSUREPUMPS
DISTANCE_WELLS
DRILLING_TIME
FLOW RATE
FLOW_RATE
FRACTURE_APERTURE
FRACTURE_AREA
FRACTURE_NUMBER
GEOTHERM
HDR_LOAD
HDR_MWe_INSTALLED
INFLOW_OTHER
INLET TEMPERATURE
N_PUMPS
OUTLET TEMPERATURE 10th YEA
OUTLET TEMPERATURE 1st YEAF
PLANT_CONSTRUCTION_TIME
POWERCONSUMPTION_PUMPS
Unit Technical Cost
0.34
0.24
0.14
0.04
20
30
40
50
60
70
80
90
100
-0.928 FLOW_RATE-\[high, N2]
File Name
chart.png
Type
Portable Network Graphics (PNG)
Export Chart
Show/Hide Comment


Realisation View of Node: [high, N2] 100 realisations
Statistics
Distribution
Time Series
Planning
Sensitivity
Graph type: Cross Plot
Parameters:
CAPEX_HDR_PLANT/MWe
CAPEX_PRESSUREPUMPS
DISTANCE_WELLS
DRILLING_TIME
FLOW RATE
FLOW_RATE
FRACTURE_APERTURE
FRACTURE_AREA
FRACTURE_NUMBER
GEOTHERM
HDR_LOAD
HDR_MWe_INSTALLED
INFLOW_OTHER
INLET TEMPERATURE
N_PUMPS
OUTLET TEMPERATURE 10th YEAR
OUTLET TEMPERATURE 1st YEAR
PLANT_CONSTRUCTION_TIME
POWERCONSUMPTION_PUMPS
PRODUCED POWER 10th YEAR
PRODUCED POWER 1st YEAR
RELATIVE_EFFICIENCY_HDR_PLANT
REPLACEMENTS_COSTS
RESERVOIR_CONDUCTIVITY
RESERVOIR_DENSITY
RESERVOIR_DEPTH
RESERVOIR_SPECIFIC_HEAT_CAPACITY
T_CONDENSOR_HDR_PLANT
T_HEATER_HDR_PLANT
WATER_DENSITY_AT0
WATER_HEAT_CAPACITY
WATER_THERMALEXPANSION
WATER_VISCOSITY
Unit Technical Cost
0.30
0.20
0.10
0.5
0.6
0.7
0.8
0.9
-0.975 RELATIVE_EFFICIENCY_HDR_PLANT-\[high, N2]
File Name chart.png
Type Portable Network Graphics (PNG)
Export Chart
Show/Hide Comment

AIM of future research →
bring UTC below 15cts/kWh



Conclusions EGS

- Fast models are available in EXCEL
- Excel spread-sheet (and DSS) to be distributed as Engine WP9 deliverable. Excel can be easily modified (no black box). DSS fully probabilistic, scenario trees etc.

- Models allow to rationalize added value of new research for exploration and production