DEEP: Economic evaluation model of Power Plant

The purpose of this report is to present the methodology for the economic evaluation of various desalination and energy source options as modelled on DEEP software. The methodology includes simplified models of several types of nuclear/fossil power plants, and both distillation and membrane desalination plants.

A specific plant can be modelled by adjustment of input data including size, cost and performance data. Output includes the levelised cost of water and power and breakdowns of cost components of each selected component.

DEEP includes calculations for the following power plants:

Energy Sources		**Power**	**Heat**
NSC	Nuclear Steam Turbine (PWR,PWHR,SPWR)	✔	✔
NBC	Nuclear Gas Turbine (GTMHR)	✔	✔
NH	Nuclear Heat (HR)		✔
COAL	Steam Cycle – Coal (SSB)	✔	✔
OIL	Steam Cycle – Oil	✔	✔
GT	Gas Turbine/HRSG	✔	✔
CC	Combined Cycle	✔	✔
FH	Fossil Heat (Boiler)		✔
RH	Renewable Heat		✔

Costs involved in the economic evaluation of energy sources are summarized below:

Capital Costs		**Operating Costs (Annual)**	
	Construction Costs	*afc*	Fuel Costs
Cecon	Add. Construction Costs	*aom*	Operation and Maintenance Costs
	Contingency Costs	*tct*	Carbon tax cost (*for fossil*)
IDCp	Interest during construction		
Cdec	Decommissioning Costs (*for nuclear*)		

1. The plant construction cost: excluding site related cost, contingencies, escalation and interest during construction. This cost is also referred to as overnight construction cost. The specific cost is put in US $/kW(e) for power plants and US $/kW(th) for heating plants. For NPPs, this cost is the main contributor to the electricity generation cost.

2. Additional site related construction cost: This may include additional estimated costs for site levelling, foundations, cooling water intake/outfall, special provisions for plant safety and environmental protection. This is usually a percentage of the above cost.

3. Contingency factor: This factor reflects uncertainties of the construction cost estimate which are not known at the time of the estimate, including provisions for additional regulatory requirements and/or cost impacts from an extended construction period. The default contingency factor of 10% would apply to a proven power plant type and size to be constructed at a qualified site. It will have to be chosen considerably higher for innovative technologies and/or sites, which were not investigated in detail.

4. Interest during construction: The time period between the first pouring of concrete and the start of commercial operation is the construction lead time. This time period depends strongly on the plant type, net output and site specific conditions. It could be about 12 months for a gas turbine plant and about 60 months for a medium or large size NPP. The construction lead-time is used to calculate the interest during construction (*IDCp*) and the real escalation of the fuel price.

5. Decommissioning cost: This includes all costs for the dismantling of a nuclear plant and for management and disposal of the decommissioning waste.

6. Fuel cost: For nuclear plants, this includes all nuclear fuel cycle costs, comprising uranium supply, enrichment, fuel fabrication and spent fuel management and disposal, in \$/MW(e)・h (or \$/MW(th)・h for heating plants).

7. Specific O&M cost: This is the non-fuel operating and maintenance cost of the energy source, including staff cost, spare parts, external assistance, insurance cost, in \$/MW(e)・h (or \$/MW(th)・h for heating plants).

Sizing variables and other exogenous parameters, that characterize a specific case, are defined in the following table.

Case-specific Input		
Power Plant Capacity	*P*	MW
Water Plant Capacity	*Wacd*	m3/d
Interest	*ir*	%
Discount Ratio	*i*	%
Fossil fuel annual real escalation	*eff*	%
Currency reference year	*Ycr*	-
Initial year of operation	*Yi*	-

All the technology-specific parameters needed for the economic model as well as their default values for each type of energy source are in the following table:

Model Parameters			FOSSIL						NUCLEAR		
			OIL	COAL	FH	CC	GT	RH	NH	NSC	NBC
Operation and Performance Data											
Construction lead time	*Le*	m	36	48	18	24	24	18	40	60	24
Lifetime of energy plant	*Lep*	yr	35	35	35	25	25	35	60	60	40
Op Availability	*App*	%	85%	85%	85%	85%	85%	85%	90%	90%	90%
Planned outage rate	opp	%	10%	10%	5%	10%	10%	5%	10%	10%	10%
Unplanned outage rate	oup	%	11%	11%	5%	11%	11%	5%	11%	11%	11%
Technology Efficiency	*Eb*	%	40%	39%	90%	53%	34%	90%		31%	42%
Specific CO2 Emmissions	*CO2e*	kg//kWh	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0
Cost Data											
Specific construction cost	*Ce*	\$/kW(e) or (t)	1200	1300	50	700	500	50	200	1700	1500
Specific fuel cost	*Csf*	\$/MWh(e) or (t)	75.89	25.44	30.4	57.0	89.89	7.87	6.00	6.00	6.00
Primary Fuel Price	*Cff*	\$/(bbl or tn)	50	75	50	50	50	30			
Specific O&M cost	*Ceom*	\$/MWh(e) or (t)	3.3	3.5	1	5.5	6.6	1	2	8.8	12
Carbon tax	*ct*	\$/t	20	20	20	20	20	20	0	0	0
Additional site related construction cost factor	*DCr*	%	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Energy plant contingency factor	*kec*	%	0	0	0	0	0	0	0	0	0
Nuclear plant decommissioning cost factor	*kdcopp*	%							30%	30%	30%

A.1. Capital Cost

First, the construction cost *Cecon* (in M$) is calculated from the given specific construction cost (*Cets*) (in $/kW(e), site related cost, unit net output and number of units. Then, the interest during construction (*IDCp*) is calculated with an approximative formula. For the approximation, it is assumed that the total construction costs are spent at mid-time of the construction period. Since the construction period *Le* is put in months, and the interest rate on an annual basis, *Le* is divided by 24 in the formula.

The *IDCp* is then added to the total construction cost for obtaining the total plant investment *Ceinv*. The fixed charge rate (capital recovery factor) *lfc* is calculated from the interest/discount rate *i* and the plant economic life *Lep*. This fixed charge rate is multiplied by the total plant investment to obtain the annual levelised capital cost *alcc*. In case of nuclear power plant decommissioning costs are added to the plant annualized capital cost.

Table 1: Energy Source Capital Costs Calculations

$Cets = Ce \cdot (1 + DCr) \cdot (1 + kec)$	Specific construction cost	(B.1)
$Cecon = P \cdot Cets$	Construction cost	(B.2)
$IDCp = Cecon \cdot \left((1 + ir)^{\frac{\mathrm{Le}}{24}} - 1 \right)$	Interest during construction	(B.3)
$Ceinv = Cecon + IDCp$	Total plant investment	(B.4)
$Cdec = kdcopp \cdot Ceinv$	Decommissioning Costs	(B.5)
$lfc(i, n) = \dfrac{i \cdot (1+i)^n}{(1+i)^n - 1}$	Capital recovery factor function	(B.6)
$alcc = Ceinv \cdot lfc(i, Lep)$	Annualized capital cost	(B.7)
$adec = kdcopp \cdot alcc$	Annualized decommissioning cost	(B.8)

A.2. Operating Costs

The fuel price per end-use energy produced is dependent on the efficiency of the power plant and the primary fuel price Eq. (B.9).

$$C_{sf} = \begin{cases} \dfrac{C_{ff}}{Eb \cdot 6500 \cdot 4.1868} \cdot 3600 & \text{COAL} \\ \dfrac{C_{ff}}{Eb \cdot 1.6471} & \text{OIL, GT, CC} \\ \dfrac{C_{ff}}{13 \cdot 1055} \cdot 3600 & \text{RH} \\ \dfrac{C_{ff}}{1.6471} & \text{FH} \\ C_{ff}\ * & \text{NSC, NBC} \end{cases} \quad \text{Specific fuel cost} \qquad \text{(B.9)}$$

**For nuclear power plants Csf is an input; no calculations based on primary fuel are made.*

Availability of the plant (*App*) is calculated by planned (*opp*) and unplanned (*oud*) outage rate of the plant. The energy produced per year (*adpr*) can then be estimated.

The fuel cost levelisation factor (*lff*) is defined as the ratio of the present values of the lifetime fuel costs, including real escalation, and the unescalated lifetime fuel costs. It is calculated from the real escalation rate of the fuel price, the real interest rate *i*, the initial year of operation and the economic life of the power plant.

The levelised cost (either electricity or heat) is calculated on an annual basis by summing up the levelised capital cost, levelised decommissioning cost (if applicable), levelised fuel and O&M cost. The total of these costs, i.e. the (levelised) annual required revenue (in M$/a), is divided by the annual energy generation (*lpc*, in kWh(e) or kWh(t)) of the base power plant.

Table 2 : Power Plant Operating Costs calculations

$App = (1 - opp)(1 - oup)$	Operating Availability	(B.10)
$adpr = P \cdot 8760 \cdot App$	Annual electricity production	(B.11)
$lff\,(i,n) = (1 + eff\,)^{Yi - Ycr} \cdot \dfrac{lfc(i,n)}{\dfrac{1+i}{1+eff} - 1} \cdot \left(1 - \left(\dfrac{1+eff}{1+i}\right)^{n}\right)$	Fuel levelisation factor	(B.12)
$afc = Csf \cdot adpr \cdot lff\,(i, Lep)$	Annual fuel cost	(B.13)
$aom = Ceom \cdot adpr$	Annual O&M cost	(B.14)
$tct = ct \cdot CO2e \cdot P \cdot 8760$	Total carbon tax	(B.15)

Table 3 : Power Plant Total annual costs

$arev = alcc + adec + afc + aom + tct$	Total annual cost ($)	(B.16)
$lpc = arev / adpr$	Levelised power cost ($)	(B.17)
$slcc = alcc / adpr$	Sp. levelised capital cost ($)	(B.18)
$sfc = afc / adpr$	Sp. fuel cost ($)	(B.19)
$som = aom / adpr$	Sp. O&M cost ($)	(B.20)
$sdec = adec / adpr$	Sp. levelised decommissioning cost ($)	(B.21)

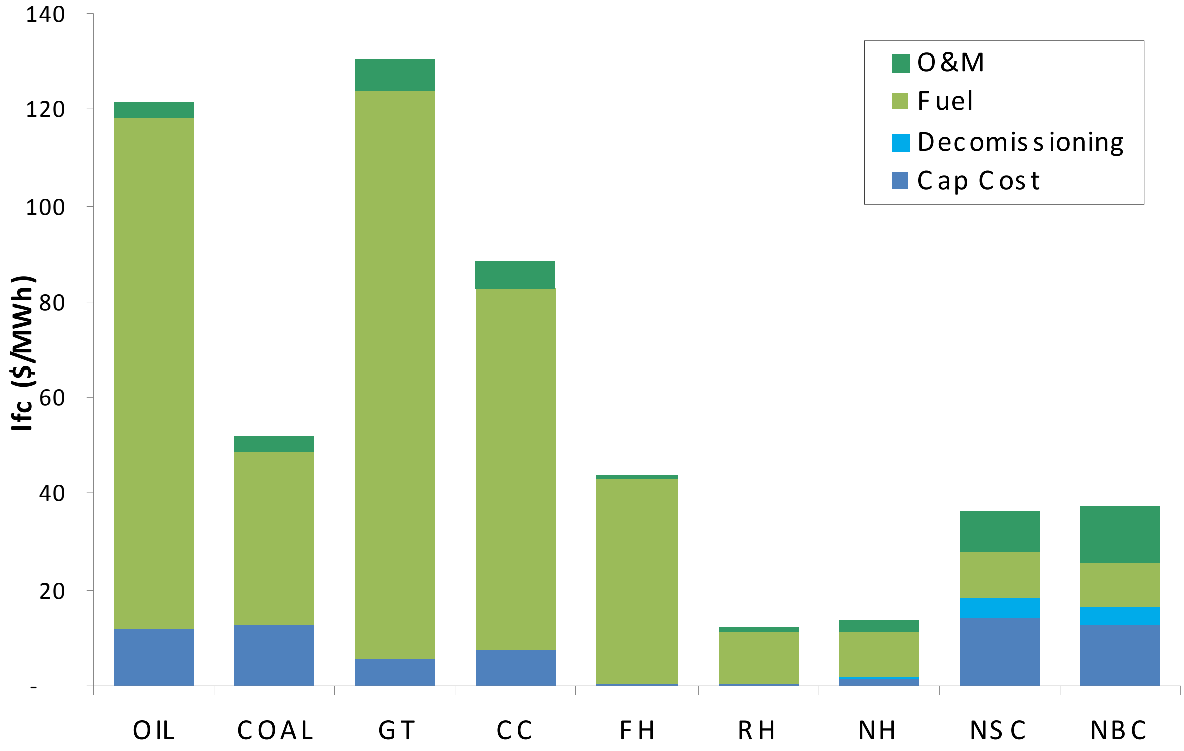
B. Remarks - Considerations

- Contingency and additional construction costs are calculated based on specific construction cost (*Ce*) whereas decommission cost estimation is based on total plant investment (*Ceinv*). Is this approach right?
- Economy of scale factor should be added: At higher capacities marginal cost is lower. Equations of capital cost should be of this form: Y=a*X^n
- *Lff*, calculation: Need to be revised: eg. When *i* = *eff*, *lff* is not defined.
- *tct* calculation based on 8760 hours and not on 8760*App (=adpr)
- Is *Yi*-*Ycr* (used only in lff calculation) independent from *Le* (used only in IDC calculation) or do they refer to the same figure?
- General remarks: More consistent calculation flow, omit logic conditions and homogenize where possible.
- Further development: Include power and water sale prices for various cost/benefit and profitability analysis of the plant : ROI, IRR, break-even analysis etc

C. Anex

C.1. Levelised annual energy cost of single purpose plants

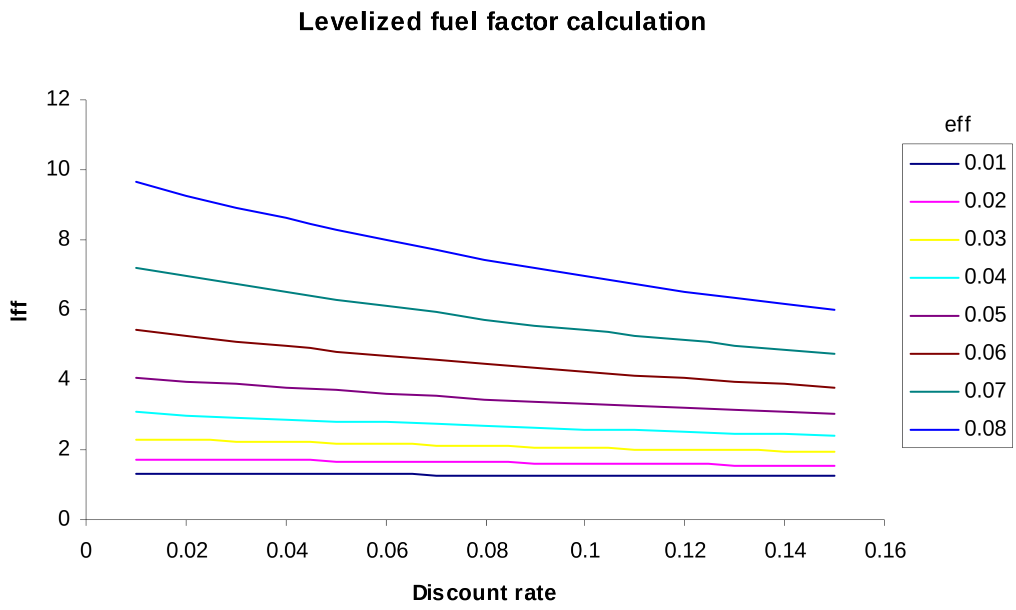
The levelised annual cost of energy for each type of power plant (applying the default parameter values) is presented in the following graph:



Calculations made for i=ir=5% and eff=2%

C.2. Calculation of levelised fuel

The graph of Equation B.12



DEEP MODEL – Review of Economic evaluation model of Power Plant

Comments by Nadira Barkatullah, *(Planning & Economic Studies Section)*

This paper gives a summary of the DEEP model economic parameters. The following comments and recommendations are therefore based on the above summary description and explanation (please refer to the item numbers, tables and description given in the above paper). It will be advisable to have a more detailed paper that clearly defines the logic behind some of the economic evaluations formulas.

Items/ Description	Comments	Recommendations
1	The terminology of the model should be consistent with the international practice. The definition of overnight cost is not correct. Overnight cost also includes owners cost and contingency costs.	Overnight cost (OC) = EPC (construction cost) + owners cost (site related cost) + contingency. The total investment cost = OC + IDC and escalation factor, if any.
2	The additional site related construction costs are generally called owners cost.	Owners cost: The default value of 10% of construction cost should be user adjustable.
3	The contingency factor should be clearly defined. For example, if we are defining contingency in terms of First-of-a-kind technology then the factor of 10% is low. OECD (2009) in their recent study has employed a factor of 5% for existing technology and 15% for new technology. For First-of-a-kind technology this factor can be upto 30% of the construction cost (The Chicago University Study 2004).	The contingency cost is generally estimated as a percentage of construction cost. The user should have the flexibility to change this parameter based on the project specific unforeseen costs.
4	What is construction lead time? The terminology should be corrected. The time period between the first pouring of concrete and the start of commercial operation is generally called 'construction	The construction duration of 60 months or 5 years for nuclear is very optimistic. This should be reconsidered in light of the type of technology.

	duration' or 'construction years'.	
Case-specific Input Table	What is meant by case 'specific input '– are these used for sensitivity analysis?	
Model Parameters Table	The model parameter data needs a careful review and update.	The user should be encouraged to input their plant specific data. It might be more appropriate to have a range of cost data, because it varies by technology, size, region/country, etc. The relevant sources are: OECD World Economic Outlook and the Projected Costs of Generating Electricity 2010.
Table 1 Energy Sources Capital Cost Calculations	The 'Cets' formula is not correct	Contingency factor or 'kec' is generally percentage of construction cost
Table 1 Energy Sources Capital Cost Calculations	IDC formula needs to be revised. The IDC is a vital component of capital cost and any approximation will impact the Levelised Unit Electricity Cost (LUEC) calculations. Based on how the actual construction takes place any approximation will over/under estimate the LUEC.	The formula for IDC in the DEEP model assumes constant construction cost each year. However, the construction cost generally vary over the construction duration, therefore a recommended formula that gives the user this flexibility is given below: $\sum_{t=i}^{ct} C_t / (1+ir)^{(t+0.5)}$ $t = -i \ldots ct(years)$
Table 1 Energy Sources Capital Cost Calculations	Annualised decommissioning costs formula 'adec' is not correct	The decommissioning cost should not be taken as percentage of total investment cost but only construction cost. The agreed percentage used in the OECD study for nuclear is 15% of construction cost, which is spread over 10 years after the plant is decommissioned. For example, if the life of the plant is 60 years, the decommissioning cost will be spread from year 61-70. In Net Present Value terms it is not a major component of the LUEC.
Operating costs	The formulas for operating cost are not clearly defined.	

	What is ‘Eb’?	
Table 2: Power Plant Operating cost	What is ‘eff’ is this the escalation factor? If yes, why is escalation factor only applied to fuel cost? The fuel levelisation factor logic is not clearly defined.	
Table 2: Power Plant Operating cost	The ‘tct’ formula or carbon tax needs an explanation. In LUEC a carbon cost is included.	Generally, The carbon cost per MWh (net) = Price of carbon (per tCO2)* Carbon content (tCO2/MWh)
General	Some of the formulas used in the DEEP model need be corrected. Others need a careful review and revision. The terminology needs to be carefully checked, revised and corrected.	The methodology and formulas needs to be well documented so that the user can understand the logic behind the calculations.