UNIVERSITÀ DEGLI STUDI FIRENZE
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Evaluation of Plant Capital Costs

The **Total Capital Investment** of a system **(TCI)** is only marginally composed of the **Purchase Equipment Cost** (**PEC**), which typically is between 15 and 40% of the Total Capital Investment (TCI).

In general:

$$TCI = \boxed{FCI} + AC = \boxed{DC + IC} + AC$$

Where:
FCI = **Fixed Capital Investment** (land purchase, buildings, purchase and installation of equipment,…)
AC = **Additional Costs**
DC = Direct Costs (equipment, buildings and all associated permanent structures)
IC = Indirect Costs (services and non-permanent structures)

Evaluation of Plant Capital Costs

(TCI)

- **(FCI)**
  - **(DC)**

    ON-SITE (**ONSC**):
    1) Costo di acquisto delle macchine (**PEC**)
    2) Costo di installazione
    3) Piping
    4) Strumentazione e sistema di controllo
    5) Collegamenti e apparecchiature elettriche

    OFF-SITE (**OFSC**):
    1) Terreno
    2) Opere civili e strutture
    3) Service facilities (ausiliari per la fornitura di combustibile, refrigeranti, ecc.)

  - **(IC)**
    1) Progettazione, supervisione, direzione lavori
    2) Costi di costruzione
    3) Contingenze (variazioni di costi, difficoltà di trasporto, eventi meteo, ecc.)

- **(AC)**
  1) Costi di avviamento (**SUC**) (modifiche necessarie per l'avviamento dell'impianto)
  2) Working capital (**WCP**) (Materie prime, combustibile, ecc. per l'avviamento)
  3) Costi di licenze, ricerca e sviluppo (**LDR**)
  4) Finanziamento durante la costruzione (**AFUDC**)

Evaluation of Plant Capital Costs

The first step is certainly the evaluation of the **Purchase Equipment Cost** (PEC). For a company it is often possible to get accurate estimates from previous projects, or to ask for a quotation.

Engineering Companies are usually able to evaluate PEC but are often reluctant to provide this info. Some softwares provide cost estimates for certain categories of equipment (e.g. Aspen Plus or Hysis for heat exchangers).

Textbooks in Chemical Engineering provide PEC evaluation charts. The estimates are often not accurate. In any case it is generally necessary to correct the chart cost data taking into account several variables, such as: design conditions (pressure, temperature,...), materials, and first of all **size of the equipment**.

Textbooks containing useful cost evaluation charts:

Garrett (Springer), **Peters-Timmerhaus** (McGraw-Hill), **Turton** (Prentice-Hall).

Turton book offers a popular spreadsheet (CapCost.xls).

Peters-Timmerhaus textbook offers a PEC calculation tool on the Web site: http://www.mhhe.com/engcs/chemical/peters/data/).

The estimates of spreadsheets or web sites are often not accurate.

Cost data from the web are useful for a check at power plant level but no disaggregation is present:

http://nyethermodynamics.com/trader/kwprice.htm

https://www.eia.gov/todayinenergy/detail.php?id=26532

Direct Cost 1 (Basis): Purchase Equipment Cost (PEC)

Estimates of Purchased-Equipment Cost

The purchased-equipment cost (C_B) can be obtained through:

- vendors' quotations
- cost estimates from past purchase orders
- quotations from experienced professional cost estimators
- cost databases maintained by engineering companies
- commercial computer programs
- estimating charts (module method)

The module cost

$$C_M = C_B\, f_d\, f_m\, f_T\, f_p\, f_{BM}$$

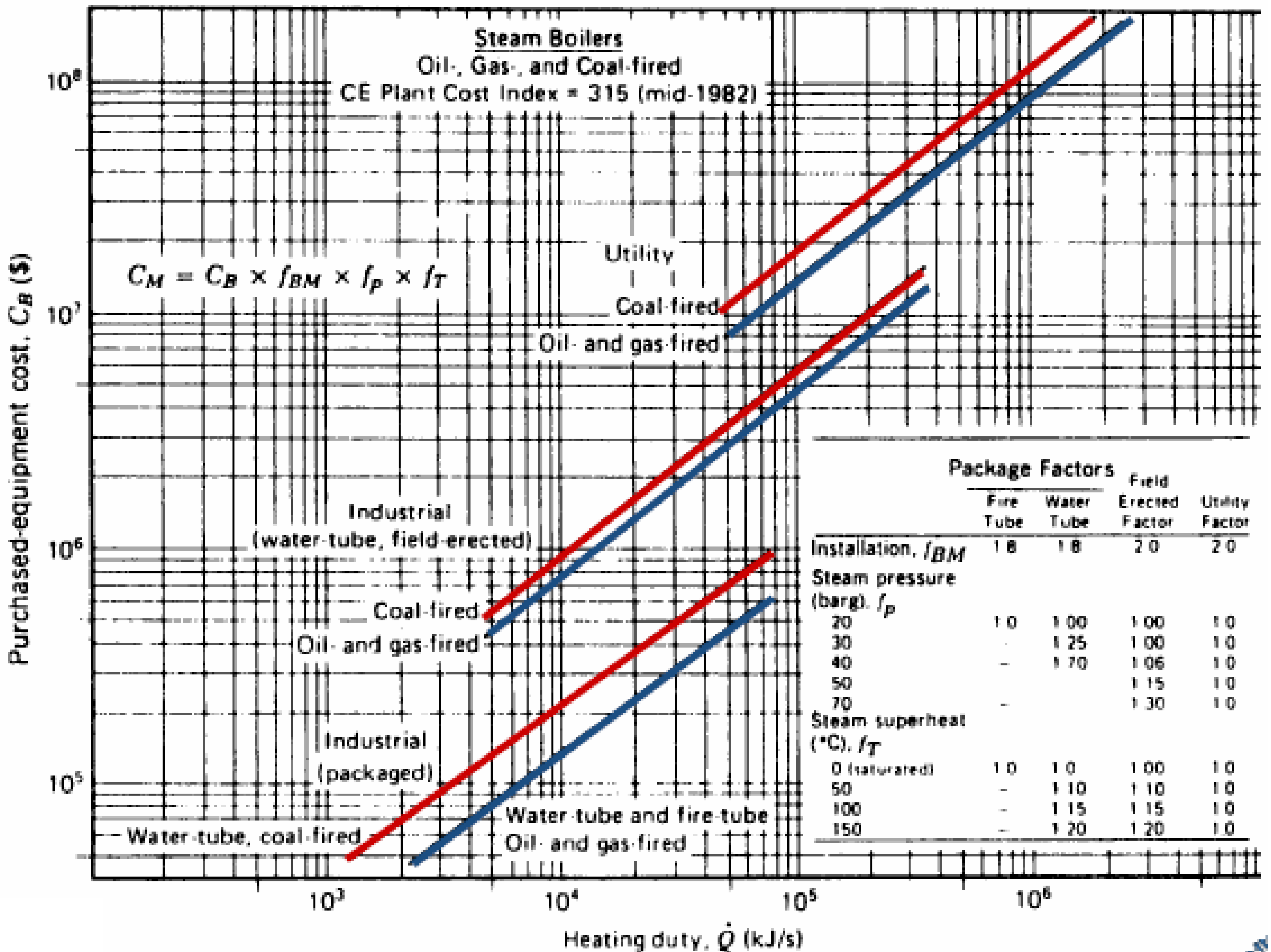
or

$$C_M = C_B\left[\left(f_d + f_T + f_p\right)f_m + f_{BM} - 1\right]$$

where

f_d – design-type factor; f_m – material factor; f_T – temperature factor;
f_p – pressure factor; f_{BM} – bare module factors

PEC Steam Boilers (chart)



Package Factors

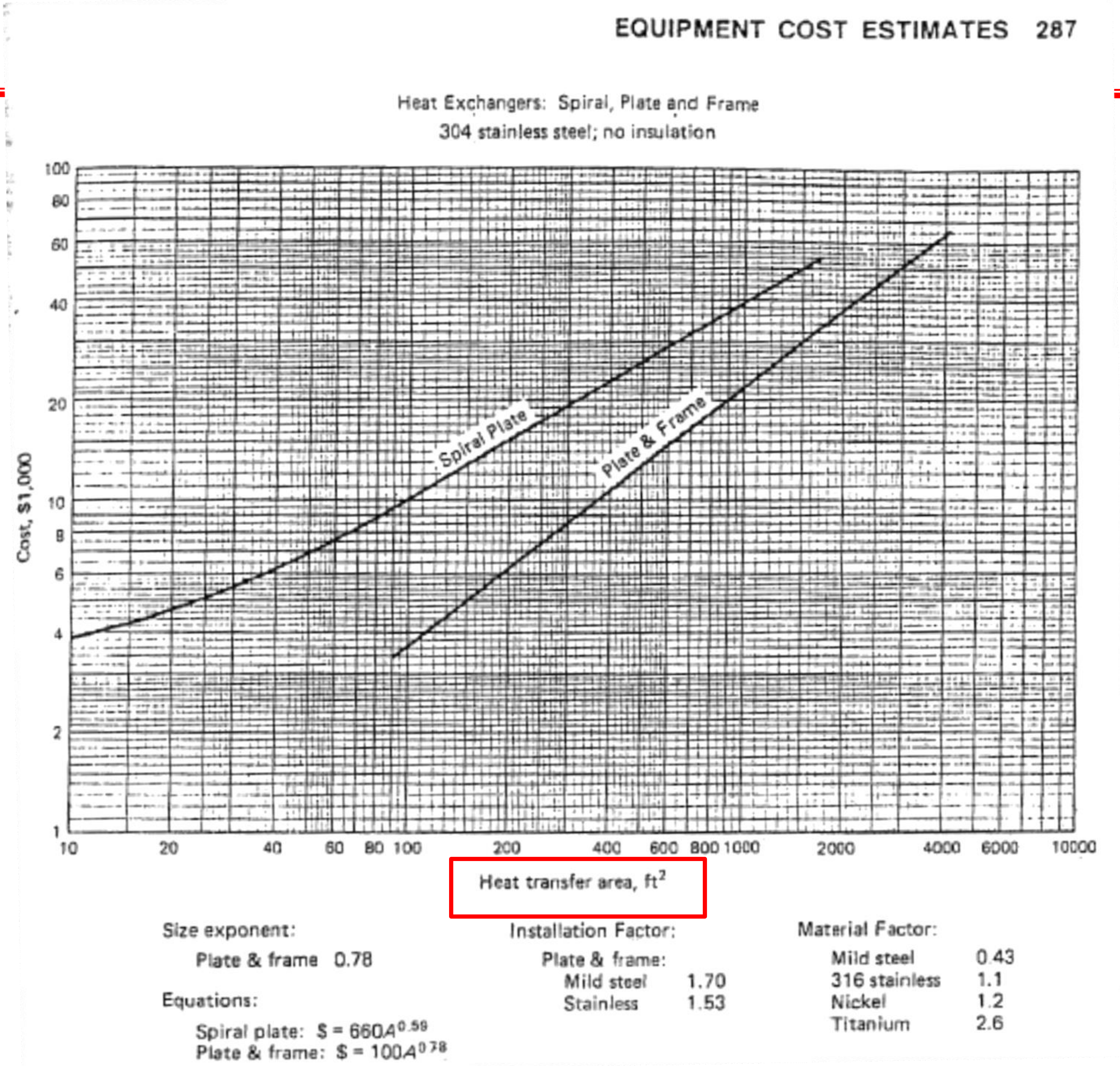
	Fire Tube	Water Tube	Field Erected Factor	Utility Factor
Installation, f_{BM}	1.8	1.8	2.0	2.0
Steam pressure (barg), f_p				
20	1.0	1.00	1.00	1.0
30	-	1.25	1.00	1.0
40	–	1.70	1.06	1.0
50			1.15	1.0
70	–		1.30	1.0
Steam superheat (°C), f_T				
0 (saturated)	1.0	1.0	1.00	1.0
50	–	1.10	1.10	1.0
100	-	1.15	1.15	1.0
150	–	1.20	1.20	1.0

PEC - HE

PEC Chart

Heat Exchangers

Cost referred to surface



PEC of Major Equipment. Pauschert, **ESMAP 2009**

Table 2.3 Estimated Costs of Major Equipment (2008 US$)

Equipment Item	Estimated Cost, US$/kW net
Pulverized Coal Boiler, subcritical, 325-MW gross	300
Pulverized Coal Boiler, subcritical, 540-MW gross	270
Pulverized Coal Boiler, supercritical, 860-MW gross	250
Steam Turbine, subcritical, 325-MW gross	130
Steam Turbine, subcritical, 540-MW gross	120
Steam Turbine, supercritical, 860-MW gross	110
Oil-Fired Boiler, subcritical, nominal 300 MW (cursory bid)	200
Gas Turbine (from large simple cycle case), 144 MW	240
Gas Turbine (from large combined cycle case), 191 MW	220
Diesel Engine-Generator, 1.4 MW	290
Diesel Engine-Generator, 4.8 MW	450

Purchase Equipment Cost (PEC): Effect of Size

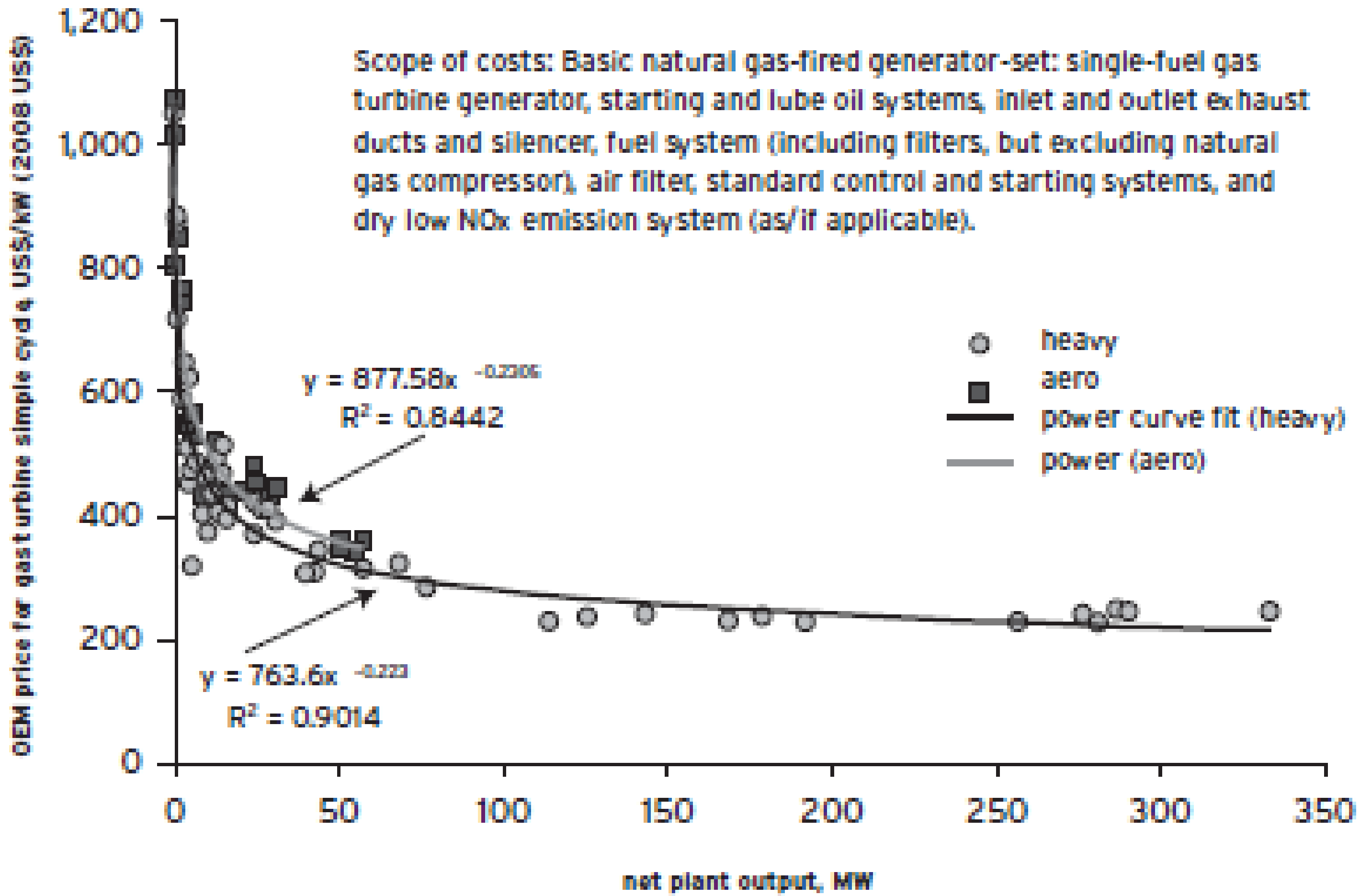
Effect of size on equipment cost

$$C_Y = C_W \left(\frac{X_Y}{X_W} \right)^{\alpha}$$

X_Y and X_w are the sizes or capacities of the equipment and C_Y and C_W are the purchase costs of the *same type* of equipment in the *same year* but with a *different size*.

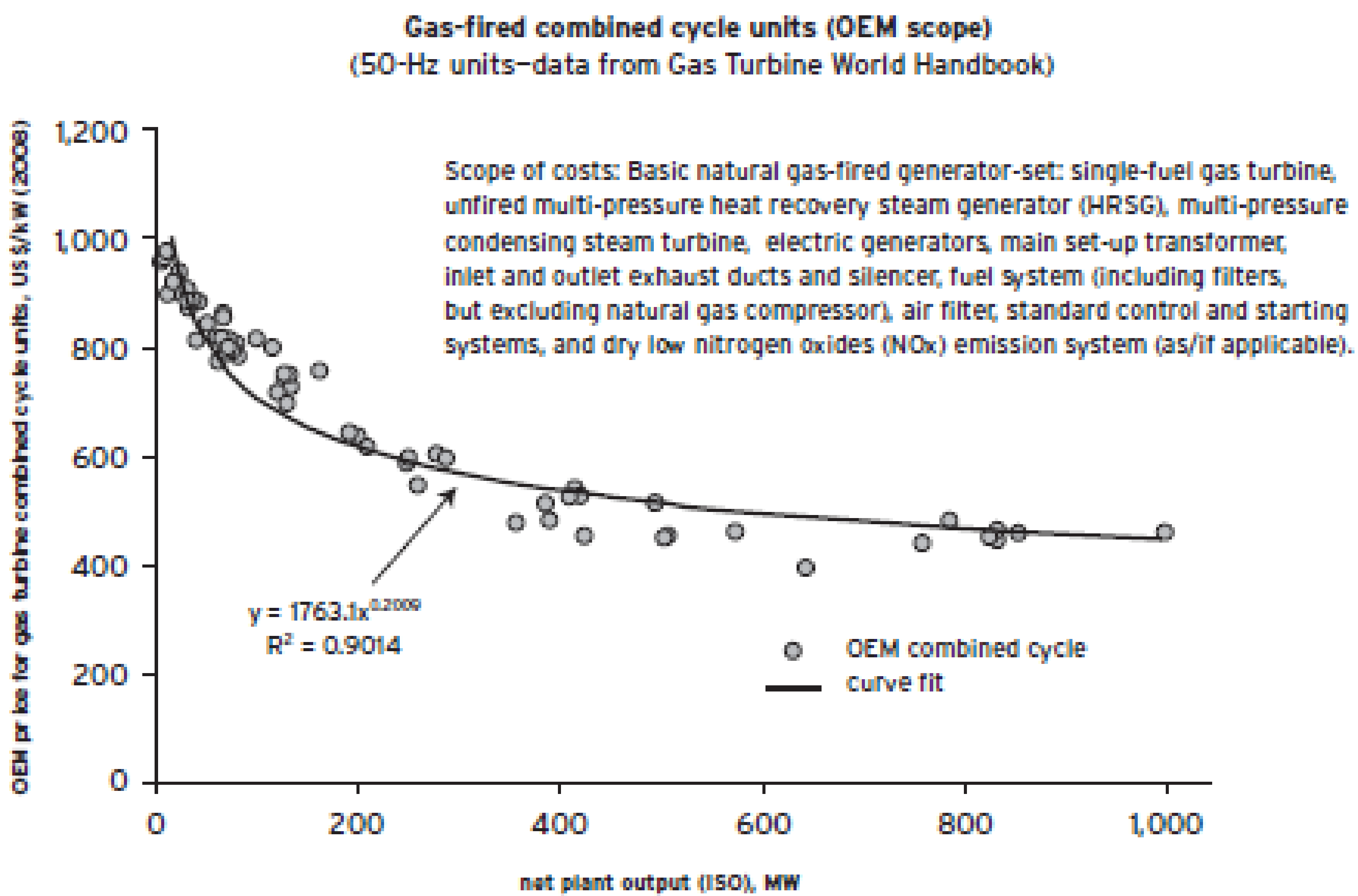
Size Effect; **GTs**. Pauschert, ESMAP 2009

Figure 4.1 Impact of Size on OEM Cost for Simple Cycle Units



Size Effect; **CCGTs**. Pauschert, ESMAP 2009

Figure 4.4 Impact of Size on OEM Costs for Combined Cycle Units



Size Effect; **CCGT 140MWe**. Cost Breakdown. Pauschert, ESMAP 2009

Table 5.4 140-MW Combined Cycle Plant–Heavy-Frame Gas Turbine

Each Item Includes Costs for Equipment, Material, and Labor (January 2008 US$)

Cost Estimate Summary	U.S. (thousands $)	India (thousands $)	Romania (thousands $)
Civil/Structural	7,240	5,130	5,280
Mechanical			
Gas Turbine (OEM Price)[1]	99,740	99,740	99,740
SCR	1,260	630	450
Gas Compressor	2,840	2,790	2,780
Electrical	9,720	8,070	7,590
Piping	9,480	6,680	8,680
Instruments and Controls	1,660	1,510	1,470
Balance of Plant/General Facilities	21,640	14,810	12,830
Total Direct Costs	153,580	139,360	138,820
Indirect Costs	13,490	4,960	3,470
Engineering and Home Office Costs	13,040	5,180	3,840
Process Contingency	0	0	0
Project Contingency	12,060	9,950	9,280
Total Plant Cost	192,170	159,450	155,410
Gas Turbine Cost (FOB-OEM), US$/kW	730	730	730
Total Plant Cost, US$/kW	1,410	1,170	1,140

Size Effect; CCGT 580MWe. Cost Breakdown. Pauschert, ESMAP 2009

Table 5.5 580-MW Combined Cycle Plant—Heavy-Frame Gas Turbine

Each Item Includes Costs for Equipment, Material, and Labor (January 2008 US$)

Cost Estimate Summary	U.S. (thousands $)	India (thousands $)	Romania (thousands $)
Civil/Structural	20,120	14,100	14,620
Mechanical			
Gas Turbine (OEM Price)[1]	262,930	262,930	262,930
SCR	3,460	1,730	1,230
Gas Compressor	3,480	3,410	3,390
Electrical	28,990	24,500	23,180
Piping	28,190	20,250	26,880
Instruments and Controls	4,300	3,890	3,760
Balance of Plant/General Facilities	46,700	34,380	30,810
Total Direct Costs	398,170	365,190	366,800
Indirect Costs	33,870	12,810	9,210
Engineering and Home Office Costs	32,750	13,380	10,210
Process Contingency	0	0	0
Project Contingency	30,280	25,690	24,660
Total Plant Cost	495,070	417,070	410,880
Gas Turbine Cost (FOB-OEM), $/kW	460	460	460
Total Plant Cost, $/kW	860	720	710

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Purchase Equipment Cost (PEC): scaling exponent α

Plant	Capacity Variable	Capacity Range	Exponent α
Air (liquid)	Product flow rate	70–4000 t/d[a]	0.66
Air plant (packaged)	Compressed dried air rate	0.1–100 Nm^3/s	0.70
Ammonia	Product flow rate	450–1800 t/d	0.58
Argon	Product flow rate	25–500 Nm^3/h	0.89
Carbon black	Product flow rate	45–900 t/d	0.67
Carbon dioxide (gas or liquid)	Product flow rate	85–920 t/d	0.72
Cogeneration plant	Net power	5–150 MW	0.75
Electric power plant	Net power	1.0–1000 MW	0.80
Ethanol	Product flow rate	$(4–40) \times 10^3$ m^3/yr	1.00
		$(40–400) \times 10^3$ m^3/yr	0.90
Liquified natural gas	Product flow rate	$(1–20) \times 10^3$ t/d	0.68
Methanol	Product flow rate	$(1.2–18) \times 10^6$ t/yr[a]	0.78
Natural gas purification	Product flow rate	18–270 t/d	0.75
Nitrogen (liquid)	Product flow rate	70–4000 t/d	0.66
Oxygen (gaseous)	Product flow rate	35–900 t/d	0.59
Oxygen (liquid)	Product flow rate	500–2700 t/d	0.37
Refinery (complete)	Feed flow rate	$(9–120) \times 10^3$ bbl/d[a]	0.86
Refrigeration unit	Cooling load	0.05–10 MW	0.70
Refuse-to-electricity	Net power	10–150 MW	0.75
Sour gas treating	Feed flow rate	0.5–16 Nm^3/d	0.84
Sulfuric acid	Product flow rate	85–1000 t/d	0.56
SNG from coal	Product flow rate	$(0.5–5.5) \times 10^6$ Nm^3/d	0.75
Wastewater treatment plant	Water flow rate	0.005–5 m^3/s	0.67
Water desalination	Water flow rate	0.05–3 m^3/s	0.89

[a] The symbols t/d and t/yr refer to metric tons per day and metric tons per year, respectively. The symbol bbl/d means barrels per day.

Purchase Equipment Cost (PEC): Year Indexing

Cost Indices

All cost data used in an economic analysis must be brought to the same reference year: the year used as a basis for the cost calculations. For cost data based on conditions at a different time, this is done with the air of an appropriate *cost index*.

C_{new} can be obtained from reference year cost data C_{ref} by using appropriate cost indices I_{new} and I_{ref} of the year of the required estimate and the reference year

$$C_{new} = C_{ref}\left(\frac{I_{new}}{I_{ref}}\right)$$

Cost indices are frequently published in several journals

Roosen Cost Functions (CCGTs; 2002)

P. Roosen, S. Unhlenbruck and L. Klaus, *International Journal of Thermal Sciences*, vol. 42, pp. 553-560, 2003

$$C_{comp} = c_{11} \cdot \dot{m}_{air} \cdot \frac{1}{c_{12} - \eta_{ss,comp}} \cdot \beta \cdot ln\,(\beta)$$

$$C_{cc} = c_{21} \cdot \dot{m}_{air} \cdot \left(1 + e^{c_{22} \cdot (T_{out} - c_{23})}\right) \cdot \frac{1}{0.995 - \left(\frac{p_{out}}{p_{in}}\right)}$$

$$C_{turb} = c_{31} \cdot \dot{m}_{gas} \cdot \frac{1}{c_{32} - \eta_{ss,turb}} \cdot \left(1 + e^{c_{33} \cdot (T_{in} - 1570\ K)}\right)$$

$$C_{ST} = c_{51} \cdot \dot{W}_{ST}^{0.7} \cdot \left(1 + \left(\frac{0.05}{1 - \eta_{ss,ST}}\right)^3\right)\left(1 + 5 \cdot e^{\left(\frac{T_{in} - 866}{10.42}\right)}\right)$$

$$C_{HRSG} = c_{41} \sum_i f_{p,i} f_{T,w,i} f_{T,g,i} \left(\frac{\dot{Q}_i}{\Delta T_{ln,i}}\right)^{0.8} + c_{42} \sum_j f_{p,j} \dot{m}_{steam,j} + c_{43} \dot{m}_g^{1.2}$$

$$f_{p,i} = 0.0971 \cdot \frac{p_i}{30\ bar} + 0.9029$$

$$f_{T,g,i} = 1 + e^{\left(\frac{T_{out,g,i} - 990\ K}{500\ K}\right)}$$

$$f_{T,w,i} = 1 + e^{\left(\frac{T_{out,w,i} - 830\ K}{500\ K}\right)}$$

$$C_{CT} = c_{61} \frac{\dot{Q}_{CT}}{k \cdot \Delta T_{ln}} + c_{62} \dot{m}_{cw} + 70.5 \dot{Q}_{CT} \left(-0.69\, ln(\bar{T}_{cw} - T_{wb}) + 2.1898\right)$$

Cooling Tower

$$C_{pump} = c_{71} \cdot \dot{W}_{pump}^{0.71} \cdot \left(1 + \frac{0.2}{1 - \eta_{ss,pump}}\right)$$

$$C_{GT,gen} = 3082 \cdot \dot{W}_{GT}^{0.58}$$

Roosen Cost Functions (CCGTs; 2002)

Air compressor:

$$C_{AC} = c_{11} \cdot \dot{m}_{air} \cdot \frac{1}{c_{12} - \eta_{sC}} \cdot \Pi_C \cdot \ln(\Pi_C)$$

$c_{11} = 44.71\ \$ \cdot (kg \cdot s)^{-1}$

$c_{12} = 0.95$

Combustion chamber:

$$C_{CC} = c_{21} \cdot \dot{m}_{air} \cdot \left(1 + e^{c_{22} \cdot (T_{out} - c_{23})}\right) \cdot \frac{1}{0.995 - p_{out}/p_{in}}$$

$c_{21} = 28.98\ \$ \cdot (kg \cdot s)^{-1}$

$c_{22} = 0.015\ K^{-1}$

$c_{23} = 1540\ K$

Gas turbine:

$$C_{GT} = c_{31} \cdot \dot{m}_{gas} \cdot \frac{1}{c_{32} - \eta_{sT}} \cdot \ln\left(\frac{p_{in}}{p_{out}}\right) \times \left(1 + e^{c_{33} \cdot (T_{in} - 1570\ K)}\right)$$

$c_{31} = 301.45\ \$ \cdot (kg \cdot s)^{-1}$

$c_{32} = 0.94$

$c_{33} = 0.025\ K^{-1}$

Heat recovery steam generator:

$$C_{HRSG} = c_{41} \cdot \sum_i \left(f_{p,i} \cdot f_{T,steam,i} \cdot f_{T,gas,i} \cdot \left(\frac{\dot{Q}_i}{\Delta T_{ln,i}}\right)^{0.8} \right) + c_{42} \cdot \sum_j f_{p,j} \cdot \dot{m}_{steam,j} + c_{43} \cdot \dot{m}_{gas}^{1.2}$$

$$f_{p,i} = 0.0971 \cdot \frac{p_i}{30\ bar} + 0.9029$$

$$f_{T,steam,i} = 1 + \exp\left(\frac{T_{out,steam,i} - 830\ K}{500\ K}\right)$$

$$f_{T,gas,i} = 1 + \exp\left(\frac{T_{out,gas,i} - 990\ K}{500\ K}\right)$$

$c_{41} = 4131.8\ \$ \cdot (kW \cdot K)^{0.8}$

$c_{42} = 13380\ \$ \cdot (kg \cdot s)^{-1}$

$c_{43} = 1489.7\ \$ \cdot (kg \cdot s)^{-1.2}$

Steam turbine:

$$C_{ST} = c_{51} \cdot P_{ST}^{0.7} \left(1 + \left(\frac{0.05}{1 - \eta_{sST}}\right)^3\right) \times \left(1 + 5 \cdot \exp\left(\frac{T_{in} - 866\ K}{10.42\ K}\right)\right)$$

$c_{51} = 3880.5\ \$ \cdot kW^{-0.7}$

Condenser and cooling tower:

$$C_C = c_{61} \cdot \frac{\dot{Q}_{Cond}}{k \cdot \Delta T_{ln}} + c_{62} \cdot \dot{m}_{CW} + 70.5 \cdot \dot{Q}_{Cond} \times \left(-0.6936 \cdot \ln(\overline{T}_{CW} - T_{WB}) + 2.1898\right)$$

$c_{61} = 280.74\ \$ \cdot m^{-2}$

$c_{62} = 746\ \$ \cdot (kg \cdot s)^{-1}$

$k = 2200\ W \cdot (m^2 \cdot K)^{-1}$

Feed water pump:

$$C_P = c_{71} \cdot P_P^{0.71} \left(1 + \frac{0.2}{1 - \eta_{sP}}\right)$$

$c_{71} = 705.48\ \$ \cdot (kg \cdot s)^{-1}$

Cost Functions: Microturbines (PoliTO)

Credits: Politecnico di Torino, Corso Prof. V. Verda (2013)

Di seguito sono riportati alcuni esempi per i componenti di una microturbina

COMPRESSORE

$$C_{AC} = \frac{c_{11} \cdot m_a}{0.9 - \eta_c} \beta \cdot \ln \beta \qquad \eta_c < 0.9$$

COMBUSTORE

$$C_{CC} = c_{21} \cdot m_a \cdot \left(1 + e^{c_{23} \cdot T_{comb} - c_{24}}\right)$$

TURBINA

$$C_{AC} = \frac{c_{31} \cdot m_g}{0.92 - \eta_t} \left(1 + e^{c_{33} \cdot TIT - c_{34}}\right) \ln \beta \qquad \eta_t < 0.92$$

SCAMBIATORE DI CALORE

$$C_{PH} = c_{41} \cdot A^{0.6}$$

HRSG

$$C_{HRSG} = c_{51} \cdot A^{0.6}$$

Similar to Roosen
(but different constants!)

C11=79 €/(kg/s)
C21=256 €/(kg/s)
C23=0.018 1/°C
C24=14
C31=532 €/(kg/s)
C33=0.036 1/°C
C34=54.4
C41=2120 €/$m^{0.6}$
C51=3250 €/$m^{0.6}$

Frangopoulos Cost Functions (Steam Power Plant; 1987)

$$Z_1 = \zeta_{11} y_1^{b_{11}} g_p g_{1\eta} g_{1T}, \qquad Z_2 = \zeta_{21} y_2^{b_{21}} g_{2\eta} g_{2T},$$

$$Z_3 = T_2(\zeta_{31} n_3 R_3 + \zeta_{32}/c_{pw}) y_{3,1}/[T_0(T_s - T_a)],$$

$$Z_4 = \zeta_{41} y_4^{b_{41}} f_{4\eta} g_{4\eta}, \qquad \Gamma_{0,k} = c_k y_{0,k} \quad (k = 1, 2, 3),$$

1

$$\zeta_{r1} = (C/3.6 \times 10^5 N)\phi_r b_{r1}, \qquad g_p = \exp[(P_1 - \bar{P}_1)/b_{13}],$$

$$g_{1\eta} = 1 + [(0.45 - \bar{\eta}_{B1})/(0.45 - \eta_B)]^{b_{14}},$$

$$g_{rT} = 1 + b_{r5}\exp[(T_1 - \bar{T}_1)/b_{r6}] \quad (r = 1, 2),$$

$$g_{r\eta} = 1 + [(1 - \bar{\eta}_{IIr})/(1 - \eta_{IIr})]^{b_{r4}} \quad (r = 2, 4).$$

Z1 - Boiler
Z2 - ST
Z3 - condenser
Z4 - pump

The firsts published

Energy Vol. 12, No. 7, pp. 563–571, 1987
Printed in Great Britain

0360-5442/87 $3.00 + 0.00
Pergamon Journals Ltd

THERMO-ECONOMIC FUNCTIONAL ANALYSIS AND OPTIMIZATION

CHRISTOS A. FRANGOPOULOS

Attala Cost Functions (CCGTs; 2001)

Component	Function
(1.2) Multi-level HRSG	$C_{\mathrm{HRSG}} = 17000\left[\sum_{i=1}^{n}\left(\frac{\dot{Q}_{\mathrm{econ}}}{\Delta T_{\mathrm{econ}}}\right)_i^{0.6} + \sum_{i=1}^{n}\left(\frac{\dot{Q}_{\mathrm{evap}}}{\Delta T_{\mathrm{evap}}}\right)_i^{0.6} + \sum_{i=1}^{2}\left(\frac{\dot{Q}_{\mathrm{sh}}}{\Delta T_{\mathrm{sh}}}\right)_i^{0.6} + \left(\frac{\dot{Q}_{\mathrm{LTE}}}{\Delta T_{\mathrm{LTE}}}\right)^{0.79}\right]$
(2) Gas turbine	$C_{\mathrm{TAG}} = 3832W^{0.71}$
(3) Steam turbine	$C_{\mathrm{TAV}} = 3\,197\,280A^{0.261} + 823.7W^{1.543}$
(4.1) Titanium condenser	$C_{\mathrm{Cond}} = 17\,769S^{0.516}$
(4.2) Copper–nickel condenser	$C_{\mathrm{Cond}} = 2296S^{0.79}$
(4.3) Alluminium–brass condenser	$C_{\mathrm{Cond}} = 162S^{1.01}$
(4.4) Stainless condenser	$C_{\mathrm{Cond}} = 1.7(162S_{\mathrm{eq}}^{1.01})$
(5.1) Condenser pump	$C_{\mathrm{P.Cond}} = 37.6W^{0.8}\left[1 + ((1-0.7)/(1-\eta_{\mathrm{iso}}))^{-0.46}\right]34.4$
(6) Generator	$C_{\mathrm{ALT}} = 3082W^{0.58}$

PERGAMON
Energy Conversion and Management 42 (2001) 2163–2172
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

Thermoeconomic optimization method as design tool in gas–steam combined plant realization

L. Attala, B. Facchini, G. Ferrara *
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Carcasci Cost Functions (CCGTs; 2016)

Turbina a Gas:

$$C_{GT} = \begin{cases} 6380.5 \cdot W_{GT}^{0.73}, W_{GT} < 50MW \\ 3968.8 \cdot W_{GT}^{0.78}, W_{GT} > 50MW \end{cases}$$

La potenza è espressa in [kW].

Turbina a vapore:

$$C_{ST} = 5075.5 \cdot W_{ST}^{0.70} \cdot \left[1 + \left(\frac{0.05}{1-\eta_{ST}}\right)^3\right] \cdot \left[1 + 5 \cdot exp\left(\frac{T_{ST,in} - 866K}{10.42K}\right)\right]$$

Condensatore:

$$C_{cond} = 248 \cdot A_{cond} + 659 \cdot m_{steam}$$

Pompa:

$$C_{pump} = 940 \cdot W_{pump}^{0.71} \cdot \left[1 + \left(\frac{0.20}{1-\eta_{pump}}\right)\right]$$

Alternatore:

$$C_{alt} = 4028.1 \cdot W_{alt}^{0.58}$$

Carcasci, C., Facchini, B., Esercitazioni di Sistemi Energetici, Esculapio, 2016

Carcasci Cost Functions (CCGTs; 2016)

Caldaia a Recupero:

$$C_{HRSG} = 5404.2 \cdot \sum_i \left\{ f_{p,i} \cdot f_{T,steam,i} \cdot f_{T,gas,i} \cdot UA_i^{0.8} \right\} +$$
$$+17500.2 \cdot \sum_i \left\{ f_{p,i} \cdot m_{steam,i} \right\} + 1948.4 \cdot m_{gas}^{1.2}$$

$$f_{p,i} = 0.0971 \cdot \frac{P_i}{30bar} + 0.9029$$

$$f_{T,steam,i} = 1 + exp\left(\frac{T_{steam,out,i} - 830K}{500K} \right)$$

$$f_{T,gas,i} = 1 + exp\left(\frac{T_{gas,in,i} - 990K}{500K} \right)$$

(Same as Roosen, 2003…?)

$$UA_i = \frac{Q_i}{\Delta T_{ml}} \left[{}^{kW}\!/_{K} \right]$$

Soltani et al. Cost Functions (CCGTs; 2013)

Air compressor

$$Z_C = \left(\frac{c_{11}\dot{m}_{air}}{c_{12}-\eta_{is,C}}\right)\left(\frac{P_{out}}{P_{in}}\right)\ln\left(\frac{P_{out}}{P_{in}}\right)$$

$$c_{11} = 75\ /(\mathrm{kg/s}),\ c_{12} = 0.9$$

Combustion and post combustion chamber

$$Z_{CC} = c_{21}\cdot\dot{m}_{air(gas)}\cdot(1+\exp(c_{22}T_{out}-c_{23}))\cdot\frac{1}{0.995-\frac{P_{out}}{P_{in}}}$$

$$c_{21} = 48.64\ /(\mathrm{kg/s}),\ c_{22} = 0.018\ \mathrm{K}^{-1},\ c_{23} = 26.4$$

Gas turbine

$$Z_{GT} = \left(\frac{c_{31}\dot{m}_{gas}}{c_{32}-\eta_{is,GT}}\right)\left(\frac{P_{out}}{P_{in}}\right)(1+\exp(c_{33}T_{in}-c_{34}))$$

$$c_{31} = 1536\ /(\mathrm{kg/s}),\ c_{32} = 0.92,\ c_{33} = 0.036\ \mathrm{K}^{-1}$$

HRSG

$$Z_{HRSG} = c_{41}\cdot\sum_i\left(f_{p,i}\cdot f_{T\,steam,i}\cdot f_{T\,gas,i}\cdot\left(\frac{\dot{Q}_i}{\mathrm{LMTD}_i}\right)^{0.8}\right) + c_{42}\cdot\sum_j f_{p,j}\cdot\dot{m}_{steam,j} + c_{43}\cdot\dot{m}_{gas}^{1.2}$$

$$f_{p,i} = 0.0971\cdot\frac{p_i}{30\ \mathrm{bar}} + 0.9029$$

$$f_{T\text{-}steam,i} = 1+\exp\left(\frac{T_{out,steam,i}-830\ \mathrm{K}}{500\ \mathrm{K}}\right)$$

$$f_{T,gas,i} = 1+\exp\left(\frac{T_{out,gas,i}-990\ \mathrm{K}}{500\ \mathrm{K}}\right)$$

$$c_{41} = 4131.8\ (\mathrm{kW\,K})^{0.8}$$

$$c_{42} = 13380\ (\mathrm{kg\,s})^{-1}$$

$$c_{43} = 1489.7\ (\mathrm{kg\,s})^{-1.2}$$

Energy Conversion and Management 76 (2013) 83–91
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A comparative exergoeconomic analysis of two biomass and co-firing combined power plants

CrossMark

S. Soltani[a], S.M.S. Mahmoudi[a,*], M. Yari[b], T. Morosuk[c], M.A. Rosen[d], V. Zare[a]

Soltani et al. Cost Functions (CCGTs; 2013)

Steam turbine

$$Z_{ST} = c_{51} \cdot \dot{W}_{ST}^{0.7} \left(1 + \left(\frac{0.05}{1-\eta_{is,ST}}\right)^3\right) \times \left(1 + 5 \cdot \exp\left(\frac{T_{in} - 866\ \mathrm{K}}{10.42\ \mathrm{K}}\right)\right)$$

$$c_{51} = 3880.5\ \ \mathrm{kW}^{-0.7}$$

Condenser and cooling tower

$$Z_{Cond} = c_{61} \cdot \frac{\dot{Q}_{Cond}}{2.2.\mathrm{LMTD}} + c_{62}.\dot{m}_{CW} + 70.5 \cdot \dot{Q}_{Cond} \times (-0.6936 \cdot \ln(\bar{T}_{CW} - T_{WB}) + 2.1898)$$

$$c_{61} = 280.74\ \ \mathrm{m}^{-2}$$

$$c_{62} = 746\ \ (\mathrm{kg\ s})^{-1}$$

Pump

$$Z_{pump} = c_{71} \cdot \dot{W}_{pump}^{0.71} \left(1 + \frac{0.2}{1-\mu_{is,pump}}\right)$$

$$c_{71} = 705.48\ \ (\mathrm{kg\ s})^{-1}$$

Air preheater

$$Z_{AP} = c_{81} \cdot A_{AP}^{0.6}$$

$$c_{81} = 4122$$

$$U = 0.018\ \mathrm{kw}/(\mathrm{m}^2\ \mathrm{K})$$

Gasifier

$$Z_{gasifier} = 1600 \cdot (\dot{m}_{dry-biomass}[\mathrm{kg/h}])^{0.67}$$

Khanmohammadi et al. Cost Functions (2015) - GTs

Air compressor :

$$Z_C = \left(\frac{C_{11}}{C_{12} - \eta_{sc}}\right) r_p \ln(r_p)$$

$$C_{11} = 71.1 \ \$/\left(\mathrm{kg\,s^{-1}}\right) \quad C_{12} = 0.9$$

Combustion chamber :

$$Z_{CC} = \left(\frac{C_{21}\dot{m}_a}{C_{22} - 0.98}\right) \times (1 + \exp(C_{32}T_{comb} - C_{24}))$$

$$C_{21} = 46.08,\ C_{22} = 0.995,$$

$$C_{23} = 0.018,\ C_{24} = 26.4$$

Gas turbine :

$$Z_{GT} = \left(\frac{C_{31}\dot{m}_g}{C_{32} - \eta_{GT}}\right) \ln\left(\frac{P_4}{P_3}\right)(1 + \exp(C_{33}T_3 - C_{34}))$$

$$C_{31} = 479.34,\ C_{32} = 0.92,\ C_{33} = 0.036,\ C_{34} = 54.4$$

Applied Thermal Engineering 91 (2015) 848–859

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Research paper

Exergoeconomic multi-objective optimization of an externally fired gas turbine integrated with a biomass gasifier

CrossMark

Shoaib Khanmohammadi*, Kazem Atashkari, Ramin Kouhikamali

Khanmohammadi et al. Cost Functions (2015)

Biomass Gassifier

Air preheater : $Z_{AP} = C_{41}\left(\frac{\dot{m}_5(h_5 - h_6)}{U\Delta T_{LM}}\right)^{0.6}$

$U = 6,\ C_{41} = 4122$

Gasifier : $Z_G = 1600(3600 \times \dot{m}_{biomass})^{0.67}$

Domestic hot water heater : $Z_{DHW} = 0.3\dot{m}_{DHW}$

Organic Rankine Cycle Components

ORC evaporator : $Z_{Ev,R} = 309.14(A_{Ev})^{0.85}$

ORC pump : $Z_{Pump,R} = 200\left(\dot{W}_{Pump}\right)^{0.65}$

ORC turbine : $Z_{Tur,R} = 4750\left(\dot{W}_{tur}\right)^{0.75}$

ORC condenser : $Z_{Cond,R} = 516.62(A_{Condnser})^{0.6}$

Liszka and Ziebik Cost Functions (CCGTs, 2009)

Compressor
$$I_C = c_1 39.5 \dot{G}_a \pi_C \ln(\pi_C), \text{USD} \quad (11)$$

Combustion Chamber
$$I_{COMB} = c_1 25.6 \dot{G}_{fg} [1 + \exp(0.018 T_{COMB} - 26.4 c_2)], \text{USD} \quad (12)$$

Gas Turbine
$$I_E = c_1 266.3 \dot{G}_{fg} \ln(\pi_E)[1 + \exp(0.036 T_{COMB} - 54.4 c_2)], \text{USD} \quad (13)$$

while

$$c_1 = 21; \quad c_2 = 1.207 \quad (14)$$

HRSG
$$I_{HRSG} = 21200 \left[\sum_n \left(\frac{\dot{Q}}{\Delta T_{log}} \right)_n^{0.6} + \sum_m \left(\frac{\dot{Q}}{\Delta T_{log}} \right)_m^{0.79} \right], \text{USD} \quad (15)$$

Steam Turbine
$$I_{ST} = 1.1 \left(3197280 A_{ST}^{0.261} + 823.7 N_{ST}^{1.543} \right), \text{USD} \quad (16)$$

Condenser
$$I_{COND} = 2870 A_{COND}^{0.79}, \text{USD} \quad (17)$$

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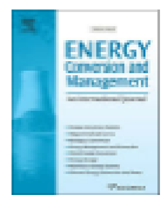

Economic optimization of the combined cycle integrated with multi-product gasification system

M. Liszka *, A. Ziebik

Cost Functions for 50 MWe Thermo-Electric Energy Storage (TEES)

Cost function of the various pieces of equipment.

Equipment	Average [kUSD 2009]	Optimistic [kUSD 2009]	Pessimistic [kUSD 2009]	Variable	Max. size of a unit
Turbine	$2\,X^{0.6}+40$	$1.5\,X^{0.6}+10$	$4\,X^{0.6}+100$	Power [kW]	–
Compressor	$9\,X^{0.6}+20$	$6\,X^{0.6}+10$	$10\,X^{0.6}+200$	Power [kW]	–
Pump	$44\,X^{0.9}+31$	$44\,X^{0.75}+20$	$50\,X+40$	Flow [m^3s^{-1}]	–
HX	$0.45\,X^{0.82}+5$	$0.3\,X^{0.82}+1$	$0.8\,X^{0.82}+10$	Area [m^2]	100000
Cold storage	$15\,X$	$10\,X$	$20\,X$	Capacity [kWh]	–
Press. vessel	$4.2\,X^{0.6}+10$	$2\,X^{0.6}+2$	$7\,X^{0.6}+25$	Volume [m^3]	5000
Tank	$0.5\,X^{0.785}+8$	$0.2\,X^{0.785}+2$	$7\,X^{0.785}+25$	Volume [m^3]	100000
Non-glass SC	$0.33\,X^{0.9}$	$0.355\,X^{0.9}$	$0.355\,X$	Area [m^2]	–
Glassed SC	$0.425\,X^{0.9}$	$0.52\,X^{0.9}$	$0.52\,X$	Area [m^2]	–
MDAC	$1.412\,X^{0.8}$	$0.941\,X^{0.8}$	$2.683\,X^{0.8}$	Area [m^2]	2000

Energy 45 (2012) 358–365

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Roundtrip Efficiency 57%

Thermoeconomic analysis of a solar enhanced energy storage concept based on thermodynamic cycles

Samuel Henchoz [a,*], Florian Buchter [b], Daniel Favrat [a], Matteo Morandin [a], Mehmet Mercangöz [b]

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[b] ABB Switzerland Ltd., Corporate Research, Segelhofstrasse 1k, CH-5405 Baden-Dättwil, Switzerland

Estimated Cost: 1200 €/kW

Special Equipment! TransCrit CO2 power cycle….

Direct Cost : Rough Estimates from PEC

Per quanto riguarda le altre componenti che costituiscono i costi diretti (DC), qualora non possano essere valutate singolarmente attraverso una dettagliata analisi, è possibile calcolarle come percentuale del costo di acquisto delle macchine (PEC). Si verificano le seguenti condizioni:

Installazione:	20-90 % del PEC
Piping:	10-70 % del PEC
Strumentazione:	6-40 % del PEC
Apparecchiature elettriche:	10-15 % del PEC
Terreno:	10 % del PEC
Opere civili:	10-80 % del PEC
Service facilities:	30-100 % del PEC

In assenza di altre indicazioni è possibile assumere il valore intermedio di ciascun intervallo.
Si sottolinea il fatto che queste valutazioni consentono di definire un ordine di grandezza del costo complessivo. L'errore commesso può essere rilevante in assenza di informazioni più dettagliate.

Credits: Politecnico di Torino, Corso Prof. V. Verda (2013)

Indirect Costs : Rough Estimates from PEC, DC and FCI

Per i costi indiretti e i costi addizionali si può procedere in modo simile a quanto visto per i costi diretti:

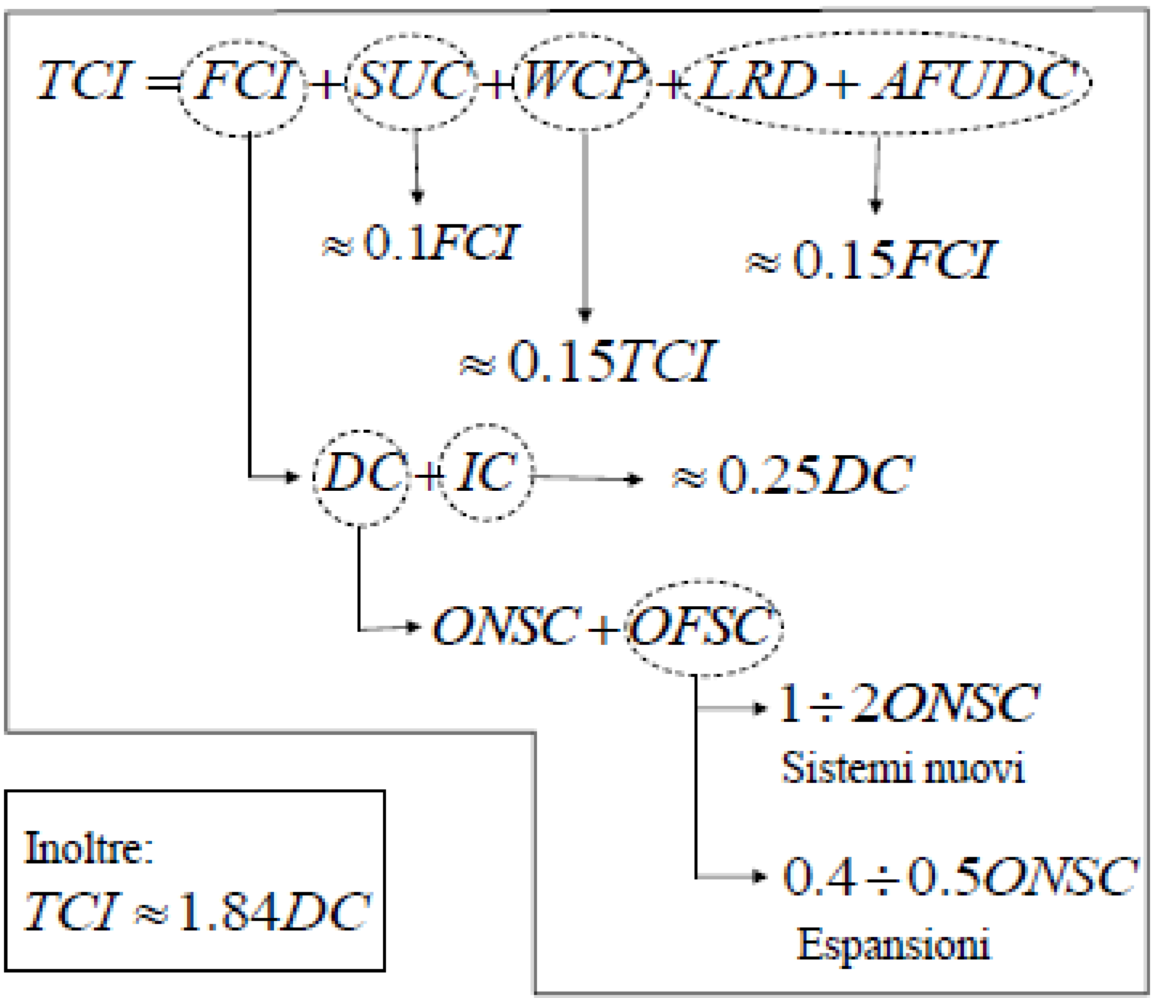
Progettazione:	25-75 % del PEC
Costruzione:	15 % del DC
Avviamento:	5-12 % del FCI
Working capital:	10-20 % del TCI

FCI = DC + IC (Recursive)

TCI = FCI + AC = DC + IC + AC (Recursive)

TCI Costs: Synthesis

E' possibile utilizzare le informazioni riportate, unitamente ad alcune valutazioni di massima delle altri componenti per fornire una relazione tra il costo di acquisizione dei macchinari (PEC) e il capitale totale associato all'investimento:



Inoltre:
$TCI \approx 1.84DC$

$TCI \approx 6.32PEC$ Per sistemi nuovi

$TCI \approx 4.16PEC$ Per espansioni di sistemi

Credits: Politecnico di Torino, Corso Prof. V. Verda (2013)

Direct Cost 1 (Basis): Purchase Equipment Cost (PEC)

Installation Cost

The *installation cost* covers the freight and insurance for the transportation from the factory, the cost for labor, unloading, handling, foundations, supports, and all other construction expenses related directly to the erection and necessary connections of the purchased equipment.

This cost is needed only when the economic analysis is conducted separately for single equipment items or small groups of items.

Credits: G. Tsatsaronis, TUB, Inspire Summer Course, 2007, Nova Gorica

Estimation of Direct Costs - 1

Piping

The cost for piping includes the material and labor costs of all items required to complete the erection of all the piping used directly in the system.

Instrumentation and Controls

The factor used to estimate these costs tends to increase as the degree of automation increases, and to decrease with increasing total cost.

Electrical Equipment and Materials

This cost includes materials and installation labor for substations, distribution lines, switch gears, control centers, emergency power supplies, area lighting, etc.

Estimation of Direct Costs - 2

Land

The cost of land strongly depends on the location and usually does not decrease with time.

Civil, Structural, and Architecture Work

This category includes the total cost for buildings, including services, as well as the costs for roads, side-walks, fencing, landscaping, yard improvements, etc.

Service Facilities

This cost includes all costs for supplying the general utilities required to operate the system such as fuel(s), water, steam, and electricity (if it is not a product of the system), refrigeration, inert gas, and sewage, waste disposal, environmental control, fire protection, and the equipment required for shops, first aid, and cafeteria.

Indirect Costs

Engineering and Supervision:

Cost for developing the detailed plan design and drawings, and the costs associated with cost engineering, scale models, purchasing, engineering supervision and inspection, administration, travel, and consultant fees.

Construction:

All expenses for temporary facilities and operations, tools and equipment, home office personnel located at the construction site, insurance, etc.

Contingencies:

Estimates are based on assumptions for cost and productivity, which may vary significantly from the actual values. The contingency factor depends on the complexity, size, and uniqueness of the energy conversion system.

Startup Costs

Startup Costs are mainly associated with design changes that have to be made after completion of construction but before the system can operate at design conditions.

The *startup costs* include

labor, materials, equipment, and overhead expenses to be used only during startup time

plus

the loss on income while the system is not operating or operating at only partial capacity during the same period.

Cost Indexing

D. Pauschert, ESMAP Technical Paper 122/09

Study of Equipment Prices in the Power Sector

Table 2.1 Historical Average Annual Compound Escalation

Ranking	Plant Equipment and Materials	Jan. 1996-Dec. 2003, % per year	Jan. 2004-Dec. 2007, % per year	Jan. 2004-Dec. 2007, % Increase for Period
	United States			
4	Ready-Mix Concrete	1.9	7.9	36
	Centrifugal Pumps	2.0	4.7	20
	Centrifugal Fans	1.7	4.2	18
	Material Handling Conveyors	1.7	4.7	20
	Pneumatic Conveyors	1.7	3.8	16
	Crushers and Pulverizers	2.9	4.4	19
	Integral Horsepower Motors	0.4	6.4	28
	Fabricated Steel Plates	0.3	10.1	47
2	Structural Steel	0.9	8.0	36
	Steel Pipe and Tubing	NA	7.0	31
	Field Erected Steel Tanks	1.5	5.8	25
3	Heat Exchangers and Condensers	0.8	7.8	35
	Fin Tube Heat Exchangers	1.3	8.4	38
	Industrial Mineral Wool	0.4	3.7	16
	Refractory, Non-Clay	0.4	3.7	16
1	Electric Wire and Cable	1.1	9.1	42
	Power and Distribution Transformers	NA	13.8	68
	Copper Wire and Cable	-0.8	18.7	98
	Industrial Process Control Instruments	NA	3.0	12
	India			
	Fabricated Metal (Structural Steel and Plate)	NA	7	31
	Steel Pipe and Tubing	NA	6	26
	Mechanical Equipment	NA	6	26
	Electric Wire and Cable	NA	20	107
	Electric Equipment	NA	7	31
	Romania			
	Fabricated Metal (Structural Steel and Plate)	NA	7	31
	Steel Pipe and Tubing	NA	5	33
	Mechanical Equipment	NA	3	13

Cost Escalation; Basic Equipment. Pauschert, ESMAP 2009

Table ES1 Historical Average Annual Compound Escalation

Ranking	Plant Equipment and Materials	Jan. 1996–Dec. 2003, % per year	Jan. 2004–Dec. 2007, % per year
	United States		
	Fabricated Steel Plates	0.3	10.1
	Steel Pipe and Tubing	NA	7.0
	Centrifugal Pumps	2.0	4.7
	Copper Wire and Cable	-0.8	18.7
	Power and Distribution Transformers	NA	13.8
	India		
	Fabricated Metal (Structural Steel/Plate)	NA	7
	Steel Pipe and Tubing	NA	6
	Mechanical Equipment	NA	6
	Electric Wire and Cable	NA	20
	Electric Equipment	NA	7
	Romania		
	Fabricated Metal (Structural Steel/Plate)	NA	7
	Steel Pipe and Tubing	NA	5
	Mechanical Equipment	NA	3

Cost Escalation; Projections, Basic Equipment.

Pauschert, ESMAP 2009

Pricing Estimates for Cost of Power Plant Technology, 2008

Table ES2 Projected Future Average Annual Compound Escalation

Plant Equipment and Materials	Projected, 2008-2012, % per year
United States	
Fabricated Steel Plates	0 to 2
Structural Steel	2 to 3
Steel Pipe and Tubing	2 to 4
Centrifugal Fans	1 to 3
Electric Wire and Cable	-1 to 2
Power and Distribution Transformers	1 to 3
India	
Fabricated Metal (Structural Steel and Plate)	6 to 8
Steel Pipe and Tubing	8 to 9
Mechanical Equipment	3 to 4
Electric Wire and Cable	1 to 3
Electric Equipment	2 to 4
Romania	
Fabricated Metal (Structural Steel and Plate)	2 to 3
Mechanical Equipment	2 to 3
Steel Pipe and Tubing	2 to 4

Table ES3 Class 5 Pricing Estimates for Selected Generation Technologies (2008 US$), US$/kW net

Generation Plant–Total Plant Cost	U.S.	India	Romania
Gas Turbine Combined Cycle Plant, 140 MW	1,410	1,170	1,140
Gas Turbine Simple Cycle Plant, 580 MW	860	720	710
Coal-Fired Steam Plant (sub), 300 MW net	2,730	1,690	2,920
Coal-Fired Steam Plant (sub), 500 MW net	2,290	1,440	2,530
Coal-Fired Steam Plant (super), 800 MW net	1,960	1,290	2,250
Oil-Fired Steam Plant (sub), 300 MW net	1,540	1,180	1,420
Gas-Fired Steam Plant (sub), 300 MW net	1,360	1,040	1,110
Diesel Engine-Generator Plant, 1 MW	540	470	490
Diesel Engine-Generator Plant, 5 MW	630	590	600

Cost Escalation; Plant Equipment. Pauschert, ESMAP 2009

Table 3.1 Average Annual Compound Escalation for Plant Equipment and Materials–United States

Figure Number	Equipment or Material Item	Jan. 1996-Dec. 2003, %/year	Jan. 2004-Dec. 2007, %/year	Projected, 2008-2012, %/year
1	Ready-Mix Concrete	1.9	7.9	2 to 4
2	Centrifugal Pumps	2.0	4.7	2 to 3
3	Centrifugal Fans	1.7	4.2	1 to 3
4	Material Handling Conveyors	1.7	4.7	1 to 2
5	Pneumatic Conveyors	1.7	3.8	NA
6	Crushers and Pulverizers	2.9	4.4	NA
7	Integral Horsepower Motors	0.4	6.4	NA
8	Fabricated Steel Plates	0.3	10.1	0 to 2
9	Structural Steel	0.9	8.0	1 to 3
10	Steel Pipe and Tubing	NA	7.0	2 to 4
11	Field Erected Steel Tanks	1.5	5.8	NA
12	Heat Exchangers and Condensers	0.8	7.8	NA
13	Fin Tube Heat Exchangers	1.3	8.4	NA
14	Industrial Mineral Wool	0.4	3.7	NA
15	Refractory, Non-Clay	0.4	3.7	NA
16	Power and Distribution Transformers	NA	13.8	1 to 3
17	Electric Wire and Cable	1.1	9.1	-1 to 2
18	Copper Wire and Cable	-0.8	18.7	NA
19	Industrial Process Control Instruments	NA	3.0	NA

Time Value of Money - 1

If P € (*present value*) are deposited in an account earning i_{eff} (*effective rate of return*) per time period and the interest is compounded at the end of each of n time periods, the account will grow to F € (*future value*)

$$F = P\left(1 + i_{eff}\right)^n$$

Credits: G. Tsatsaronis, TUB, Inspire Summer Course, 2007, Nova Gorica

Time Value of Money - 2

Single-payment compound-amount factor

$$\frac{F}{P} = \left(1 + i_{eff}\right)^n$$

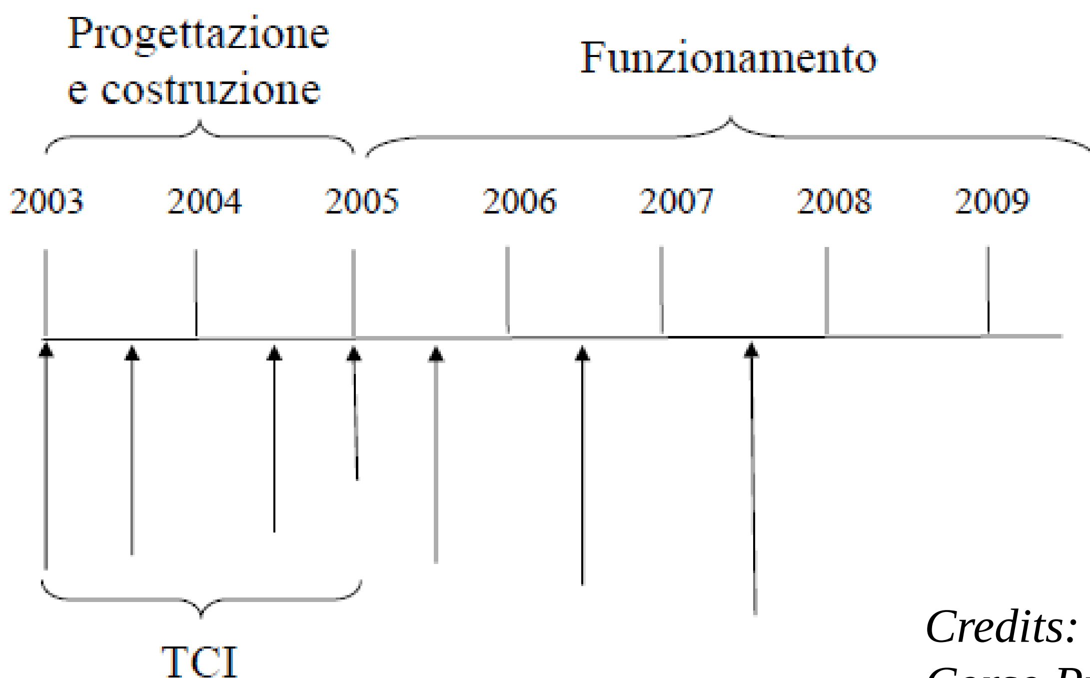
Single-payment present-worth factor (or single-payment discount factor)

$$\frac{P}{F} = \frac{1}{\left(1 + i_{eff}\right)^n}$$

Evaluation of Investment in Time

Matematica Finanziaria

La formulazione precedente può essere utilizzata per riportare all'istante 0, istante di inizio dell'attività produttiva, movimenti di denaro che avvengono nel periodo precedente (cioè le componenti che costituiscono TCI) oppure nel periodo successivo

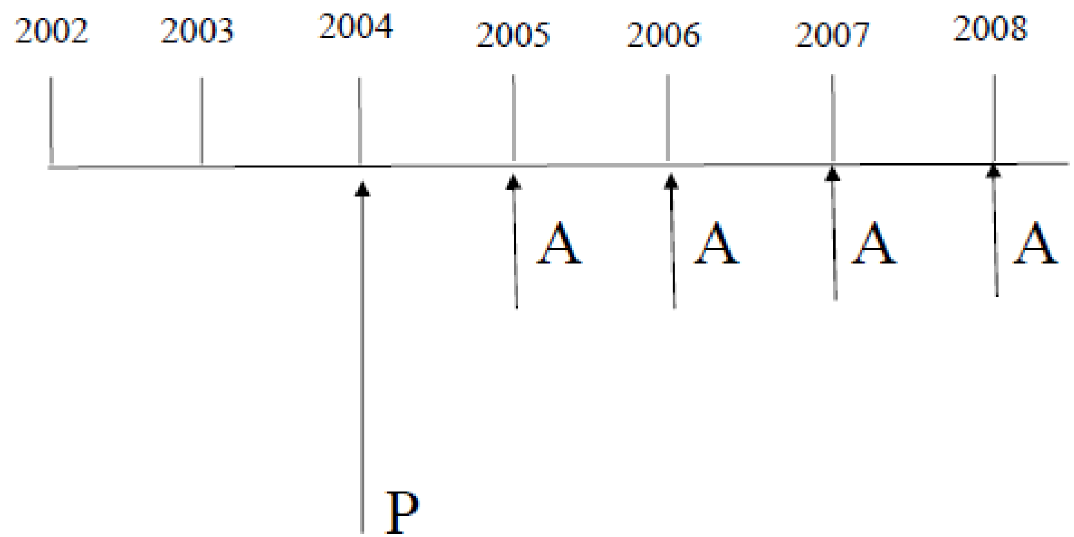


Credits: Politecnico di Torino, Corso Prof. V. Verda (2013)

Reduction of Annualities to Present Value

Annualità: rate costanti (A), pagate alla fine di ciascun periodo per n periodi. Il capitale, pagato in un'unica soluzione all'istante presente, corrispondente alle n annualità è:

$$P = A\frac{(1+i)^n - 1}{i \cdot (1+i)^n}$$



Uniform-series present-worth factor

$$\frac{P}{A} = \frac{\left(1+i_{eff}\right)^n - 1}{i_{eff}\left(1+i_{eff}\right)^n}$$

Component cost per unit time

Per il calcolo del rateo di costo Z (in €/s) si procede secondo i passi di seguito indicati:

1) Calcolo del costo C dei componenti

2) Calcolo del costo totale di investimento TCI per ciascun componente

3) Calcolo delle annualità A utilizzando la formulazione

$$A_j = TCI_j \frac{i \cdot (1+i)^n}{(1+i)^n - 1}$$

4) Calcolo rateo Z

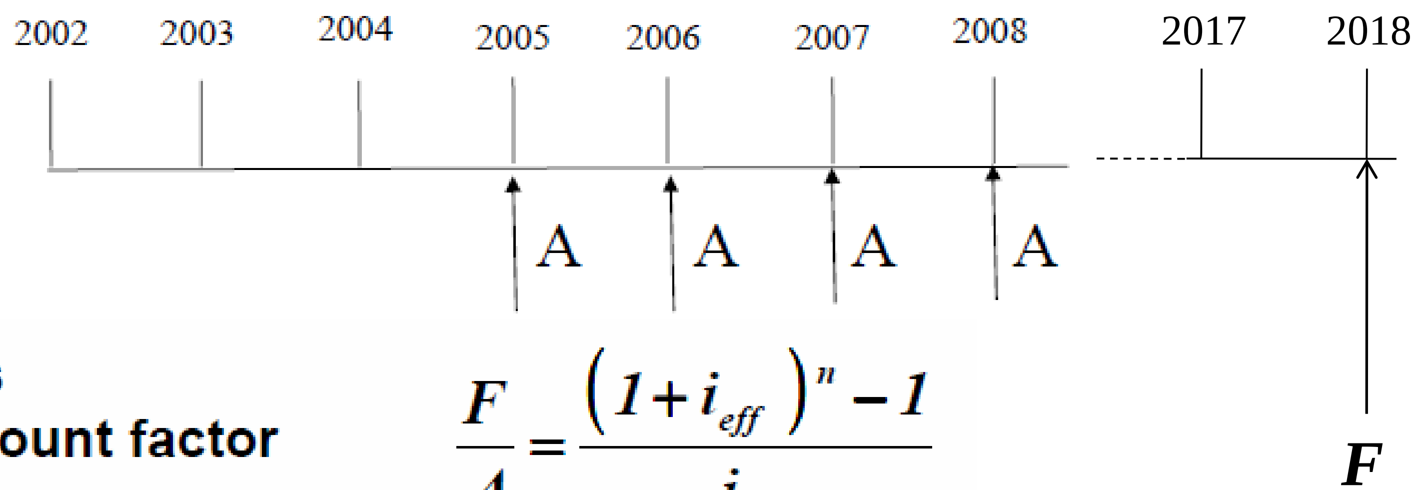
$$Z_j = \frac{A_j}{h \cdot 3600}$$

Essendo h il numero di ore equivalenti di funzionamento annue

Reduction of Annualities to Future Value

In alternativa, il capitale all'istante n corrispondente alle annualità pagate è:

$$F = A\frac{(1+i)^n - 1}{i}$$



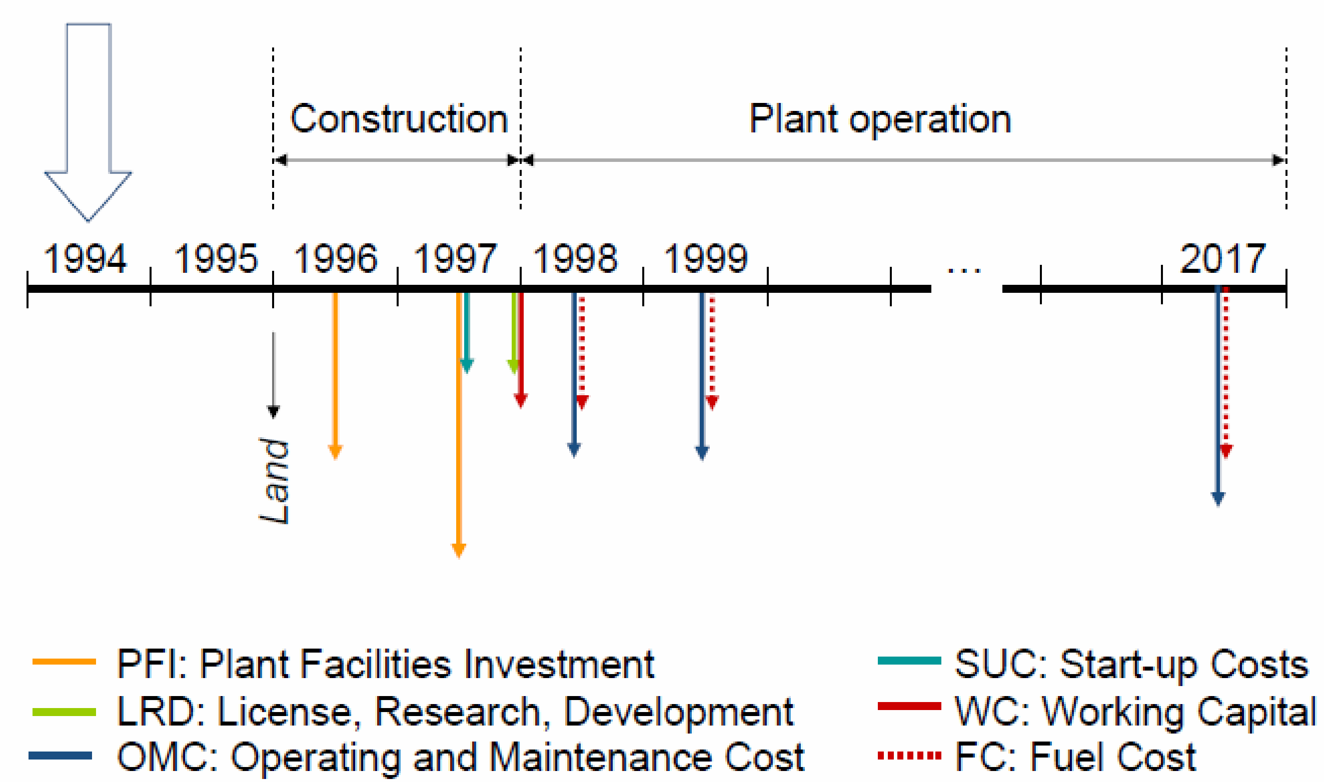
Uniform-series compound-amount factor

$$\frac{F}{A} = \frac{\left(1+i_{eff}\right)^n - 1}{i_{eff}}$$

The Payback Period **(=** ***Payout Period*** **) is defined as the length of time required for the cash inflow received from a project to recover the original cash outlays required by initial investment.**

Expenses vs. Revenues Balance

All expenses, taking place at beginning, intermediate or annual conditions, must be reduced to a common basis for evaluation of the investment (P, F or A). The same holds for yearly incomes when the plant starts production.



The preceding formulas allow to do that.

Discounted Cash Flows: NPV and IRR

Methods using discounted cash flows consider the time value of money and all cash flow streams during the life of a Project:

- Net Present Value Method (NPV)
- Internal Rate of Return Method (IRR)

Net present value method

The following rules apply: accept any project for which the present value is positive; reject any project with negative present value; projects with the highest present value are given the highest preference among various alternatives; if two projects are mutually exclusive, accept the one having the greater present value.

Internal rate of return method

It seeks to avoid the arbitrary choice of an interest rate. It calculates an interest rate, initially unknown, that is internal to the project.

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