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A Concise Capital Investment Cost Model for Gas Turbine Systems Useful in Energy Systems Education

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A Concise Capital Investment Cost Model for Gas Turbine Systems Useful in Energy Systems Education

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Introduction

Education for energy systems students is incomplete without practicing techno-economic analysis (TEA). This analysis requires at a minimum (1) capital cost or investment estimation, (2) operating cost analysis, and (3) engineering econ analysis. In energy system the operating expense is generally dominated by the cost of fuel or analogous inputs, but other operating and maintenance (O&M) costs should be included. Estimating the energy-based component of the operating cost is probably most familiar and comfortable for undergraduate students. Straightforward system analysis or simulation is adequate to support estimating the energy consumption. Usually, the intermediate result in popular mechanical engineering instructional topics is the energy efficiency or other input/output ratio of the system, from which the annual consumption of fuel, electricity, or other input can be calculated. If a current year unit cost for the energy or feedstock input and an estimate of the annual runtime are available, the initial annual energy cost can be readily evaluated. A more subtle task is estimating the other O&M costs such as labor, supplies, repair parts, taxes, insurance, etc. This task typically requires some historical information at least for similar systems or some other reasonable generic estimation. Simple engineering economic analysis adequate for undergraduate education can be relatively straightforward once a suitable economic scenario is assumed. This simple scenario includes inflation rates for the annual costs, the Minimally Acceptable Rate of Return (MARR) for present worth analysis, and crucially the economic planning period or “economic lifetime” of the system. The economic scenario largely determines if a more efficient and consequently more expensive system is worthwhile economically. Consequently, any thermal energy design exercise requires an adequate means to estimate the required “capital expenditure”, commonly called the CAPEX in recent literature and practice. So, some efficient means to estimate the CAPEX is vital to a realistic but feasible analysis and design exercise or project.

Background

Capital cost or CAPEX data to assist design engineers has been assembled at several levels of detail, specifically: (1) System Costs, (2) Modular Costs, (3) Unit Costs, and (4) Detailed Costing. Integral or System costs are interesting and useful in high level planning and in simple instructive engineering econ examples useful early in a design-oriented course. Unit Costs are actually fully weighted costs (for example, piping) including labor and overhead and typical auxiliaries (such as supports and insulation for piping) normalized to a unit of construction. The straightforward and relatively safe application of the Unit Cost approach should be distinguished from very challenging and time-consuming Detailed Costing, which requires exhaustive Work Breakdown Statements and Bills of Materials at a minimum. While Unit Costs are interesting in some courses and related practice such as HVAC engineering, Detailed Costing is best avoided except when attempted in semester long design courses. In an introductory course, however, students should be cautioned about reliance on Detailed Costing, especially about its tendency to be biased low.

Exponential cost models are especially useful **Modular Costing**, where a module is defined as a specific functional or support sub-system. A typical modular cost formula, which can be presented in product form, is

$$C_{\mathrm{M,ACT}} = C_{\mathrm{M,0,i0}} \left(\frac{R}{R_0} \right)^{\beta} \left(\frac{\mathsf{P}_1}{\mathsf{P}_{10}} \right)^{\theta_1} \left(\frac{\mathsf{P}_2}{\mathsf{P}_{20}} \right)^{\theta_2} \frac{I_{\mathrm{i}}}{I_{\mathrm{i0}}} \tag{1}$$

Or in words (for nomenclature or an all-text abstract)

The Total Modular Cost for module M for current year i =
Base Case Cost for base case year i0 x ((size ratio)^scaling exponent)
x ((premium ratio)^cost exponent) x ((current year cost index) / (base year cost index))

Note the importance of identifying the pertinent size or rating feature or design variable *R*, and any premium features such as operating temperature or pressure, symbolized by a P. Note that a symbol, distinctive from *P* for pressure, is used for a generic premium feature.

This type of modular cost model with scaling exponents appears to have been if not pioneered then certainly widely popularized by Peters and Timmerhaus [1], and authors such as Chase [2] have extended and further developed the technique. In the proposed poster presentation, exponential cost models will be presented for the usual components in a generic Brayton Cycle power plant. For coursework application, a more convenient form assumes the base case cost has already been adjusted for possible inflation giving:

$$C_{\mathrm{M,ACT}} = \left(C_{\mathrm{M,0,i0}} \frac{I_{\mathrm{i}}}{I_{\mathrm{i0}}} \right) \left(\frac{R}{R_0} \right)^{\beta} \left(\frac{\mathsf{P}_1}{\mathsf{P}_{10}} \right)^{\theta_1} \left(\frac{\mathsf{P}_2}{\mathsf{P}_{20}} \right)^{\theta_2} = C_{\mathrm{M,0}} \left(\frac{R}{R_0} \right)^{\beta} \left(\frac{\mathsf{P}_1}{\mathsf{P}_{10}} \right)^{\theta_1} \left(\frac{\mathsf{P}_2}{\mathsf{P}_{20}} \right)^{\theta_2} \tag{2}$$

A simple cycle combustion turbine power plant was the original basis for the modular costs. Obviously, the actual costs at the needed detail from an industrial supplier even if available would be highly proprietary. Instead, the base case modular costs were obtained from a published system level cost report [3] disaggregated by estimating the fractional costs for each component. The disaggregation is represented by a fractional multiplier for each component. This disaggregation makes the proposed method adaptable to the numerous examples for which only total system costs are available. The result is then

$$C_{\mathrm{M,ACT}} = \left(F_{\mathrm{M}} C_{\mathrm{SYS,0}} \right) \left(\frac{R}{R_0} \right)^{\beta} \left(\frac{\mathsf{P}_1}{\mathsf{P}_{10}} \right)^{\theta_1} \left(\frac{\mathsf{P}_2}{\mathsf{P}_{20}} \right)^{\theta_2} = C_{\mathrm{M,0}} \left(\frac{R}{R_0} \right)^{(F_{\beta}\beta)} \left(\frac{\mathsf{P}_1}{\mathsf{P}_{10}} \right)^{\theta_1} \left(\frac{\mathsf{P}_2}{\mathsf{P}_{20}} \right)^{\theta_2} \tag{3}$$

This estimate was reviewed and revised by an experienced engineer from industry who was familiar with the overall costing of such systems, and the resulting fractions were assessed to be reasonably accurate for this educational use. This result might be expected since even a relatively naïve estimate is likely to be accurate well withing an order of magnitude and therefore adequate for instruction or even a very initial conceptual cost estimate for scoping or proposal repurposes.

Scaling exponents were obtained from the process engineering literature and normalized using data from a recent publication that provides reliable costs for similar combustion turbines of several sizes [2]. The scaling exponent, beta, for an overall gas turbine system is estimated by linear regression as having around 0.6 value. This value is close to the 0.7 "rule of thumb" estimate assumed by many utility engineers, a value which appears to be well established with respect to the electric power industry. Note in the cost models, the scaling exponent has been multiplied by a factor, F_β, common to all models being applied in a system model. This factor allows the modular costs to be modified to match the probably better-established system-level scaling exponent. In this simplest model in this example the modification was not necessary.

Premium cost exponents are more challenging but are needed to access the additional costs for features that increase energy efficiency. In this context the most important premium costs are the turbine inlet temperature and the compressor pressure ratio. A brief and readily available data base for the costs of high temperature alloys was used to estimate the premium cost exponent for temperature [4], and a semi-quantitative design-based estimate was used to estimate the premium cost estimate for pressure ratio. Note that the reference [4] is an excellent practical example of a cost engineering database (CEDB) that is ideal for students since it is in the public domain and readily available online.

Example Cost Model

In its simplest form this method has been applied to a simple combustion turbine system model. This simple includes the usual compressor and turbine and either an external heat exchanger or a simplistic calorimetric model for fuel energy input, which is characterized by the Lower Heating Value of the assumed gaseous fuel. Brief descriptions of the various models follow.

For the compressor, the obvious rating feature, widely used in CEDB literature is the inlet volumetric flow. A scaling exponent of 0.75 was estimated from data in the CEDB [4]. In addition, the cost of any compressor is heavily influenced by the operating pressure ratio. A suitable cost model for a compressor is then:

$$C_{\mathrm{COMP,ACT}} = \left(F_{\mathrm{COMP}} C_{\mathrm{SYS,0}}\right)\left(\frac{\dot{V}_{\mathrm{IN}}}{\dot{V}_{\mathrm{IN,\,0}}}\right)^{\left(F_\beta\, \beta_{\mathrm{COMP}}\right)}\left(\frac{P_R}{P_{R,0}}\right)^{\theta_{PR}} \tag{4}$$

For the combustor, the physically obvious rating feature is the heating rate flow. Presumably this rate is roughly proportional to the component volume while the cost should be roughly proportional to the area. The typical sizing exponent in such a case is around 0.6 from basis analysis. A suitable cost model for a compressor is then:

$$C_{\mathrm{COMB,ACT}} = \left(F_{\mathrm{COMB}} C_{\mathrm{SYS,0}}\right)\left(\frac{\dot{Q}_{\mathrm{IN}}}{\dot{Q}_{\mathrm{IN,0}}}\right)^{\left(F_\beta\, \beta_{\mathrm{COMB}}\right)} \tag{5}$$

It is worth mentioning that the combustor may be replaced by an external heat exchanger (EXHX) in many important applications such as in high temperature gas cooled reactors and similar systems. In tis case the obvious rating feature is the heat exchange area or the essentially equivalent and easier to calculate overall conductance. In this case the cost model would be such as:

$$C_{\text{EXHX,ACT}} = \left(F_{\text{EXHX}} C_{\text{SYS,0}}\right)\left(\frac{UA}{UA_0}\right)^{\left(F_\beta \beta_{\text{EXHX}}\right)} \tag{6}$$

System level cost data that can be disaggregated to identify the cost of an EXHX may not be as readily available in this case the instructor or students will need to generate a base case cost; furthermore, the relatively high operating temperature of some heat exchangers in gas power, such as a recuperator as well as the EXHX, maybe require attention to the operating temperature. An alternative more generic heat exchanger model is then

$$C_{\text{HX,ACT}} = \left(C_{\text{HX,0}}\right)\left(\frac{UA}{UA_0}\right)^{\left(F_\beta \beta_{\text{HX}}\right)}\left(\frac{T_{\text{HX}}}{T_{\text{HX,0}}}\right)^{\theta_T} \tag{7}$$

For the turbine, the physically obvious rating feature is the turbine power. It appears that a typical sizing exponent for a flow machine is around 0.75, so this value is used here as well. While the flow characteristic in a turbine may make it relatively insensitive to the pressure ratio, a turbine in a combustion system is highly sensitive to the turbine inlet temperature. Consequently, a suitable cost model for a turbine is:

$$C_{\text{TURB,ACT}} = \left(F_{\text{TURB}} C_{\text{SYS,0}}\right)\left(\frac{\dot{W}_{\text{TURB}}}{\dot{W}_{\text{TURB,0}}}\right)^{\left(F_\beta \beta_{\text{TURB}}\right)}\left(\frac{T_{\text{TIN}}}{T_{\text{TIN,0}}}\right)^{\theta_{\text{TIN}}} \tag{8}$$

Finally, the very important Balance of Plant (BOP) cost must be considered. In some case the BOP cost may be nearly constant, an instructive situation that demonstrates one reason why relatively small systems can have disadvantageous economies of scale. In the current application data from [3] indicate that the BOP scales up slowly with electrical power with 0.5 as a representative scaling exponent. A suitable cost model is then

$$C_{\text{BOP,ACT}} = \left(F_{\text{BOP}} C_{\text{SYS,0}}\right)\left(\frac{\dot{W}_{\text{NET}}}{\dot{W}_{\text{NET,0}}}\right)^{\left(F_\beta \beta_{\text{BOP}}\right)} \tag{9}$$

The overall cost model following the pattern above has been coded in a popular equation solving software package. An example computer subroutine coded in the procedural language of a popular equation-based modeling program is appended. Since this programming language is relatively generic, the text in the appended subroutine should be readily repurposed in any typical modeling language.

Conclusion

Further results and details will be presented in the finalized poster including interesting information being developed from current engineering, purchasing, and construction management (EPCM) activities on an ongoing international concentrator solar power (CSP) project. The proposed poster is offered to assist instructors in undergraduate thermal systems analysis and design courses and possibly to guide or stimulate further student research on cost engineering for thermal energy and thermal power systems.

Table of Nomenclature	
$C_{M,ACT}$; $C_{M,0}$	Actual and Baseline cost for module M
R; R_0	Actual and Baseline Rating or Capacity for Sizing
$F_\beta\ \beta_M$	Scaling exponent for module M with system level modifier F_β
P, P_0	Actual and Baseline Premium cost feature
θ_P	Influence exponent for premium feature P

References:

[1] H. P. Loh, J. Lyons and C. W. White, "Process Equipment Cost Estimation," NETL, Morgantown, WV, 2002.

[2] CHP Partnership, "Catalog of CHP Technologies: Section 3. Combustion Turbines," US EPA, Washington, 2005.

[3] J. D. Chase, "Plant Costs vs. Capacity: A New Way To Use Exponents," *Chemical Engineering,* pp. 113-118, 6 April 1970.

[4] M. S. Peters and K. D. Timmerhaus, Plant Design and Economics for Chemical Engineers, McGraw-Hill, 1968.

Appendix: Example Subprogram for Cost Calculation

```
Procedure costing(W_dot_net, V_dot_comp, P_r, W_dot_turb, T_tin_K, T_ECM_H_K,
UA_HX, Q_dot_H : &
    Cost_comp, Cost_turb, Cost_comb, Cost_BOP, Cost_TOT, cost\KW)
$Common h_0, s_0, T_0

// base case total cost
C_0_total=20e6[$]
// Fractional cost of each module
FC_0_comp=0.30
FC_0_comb=0.15
FC_0_turb=0.35
FC_0_BOP=0.20

// Cost calculations for the compressor module
C_0_comp=FC_0_comp*C_0_total
R_0_comp=40[m^3/s]                "base case rating"
PR_0_comp=16   "base case Pressure Ratio"
Beta_comp=0.75  "scaling exponent for compressors"
Cost_comp=(C_0_comp)*(V_dot_comp/R_0_comp)^Beta_comp *(P_r/PR_0_comp)^1.4
```

```
// Cost calculations for the turbine module; all variables are analogous to the compressor
C_0_turb=FC_0_turb*C_0_total
R_0_turb=30*1000[kW]
T_0_turb=900[K]
Beta_turb=0.75    "assume same beta for FM"
Cost_turb=(C_0_turb)*(W_dot_turb/R_0_turb)^Beta_turb *(T_tin_K/T_0_turb)^1.4

// Cost calculations for the combustor module; all variables are analogous to the compressor
C_0_comb=FC_0_comb*C_0_total
R_0_comb=30*1000[kW]
Beta_comb=0.7
Cost_comb=C_0_comb*(Q_dot_H/R_0_comb)^Beta_comb

// Cost calculations for External Heat Exchanger if applied
// included as example of a heat exchanger cost calculation
// a severe penalty for very high temperature operation is likely
{C_0_EXHX=C_0_comb
R_0_EXHX=90[kW/K]
Beta_EXHX=0.9
Cost_EXHX=(2.5e6[$])*(UA_HX/R_0_EXHX)^Beta_EXHX}

// Cost calculations for alternative BOP module
// Example in which a constant unit cost is appropriate
c_unit_BOP=200.0[$/kW]          "showing an alternative unit cost here, no scaling"
Cost_BOP_alt=W_dot_net*c_unit_BOP "not used in this application"

// Cost calculations for the BOP module; all variables are analogous to the compressor
C_0_BOP=FC_0_BOP*C_0_total
R_0_BOP=10*1000[kW]
Beta_BOP=0.5
Cost_BOP=C_0_BOP*(W_dot_net/R_0_BOP)^Beta_BOP

Cost_TOT = Cost_comp+Cost_turb+Cost_comb+Cost_BOP
cost\KW=Cost_TOT/W_dot_net

FCost_comp=Cost_comp/Cost_TOT
FCost_turb=Cost_turb/Cost_TOT
FCost_comb=Cost_comb/Cost_TOT
FCost_BOP=Cost_BOP/Cost_TOT
FCost_sum=FCost_comp+FCost_turb+FCost_comb+FCost_BOP

// gas turbine cost only
Cost_GT=Cost_comp+Cost_turb+Cost_BOP
cost.GTKW=Cost_GT/W_dot_net
End
```