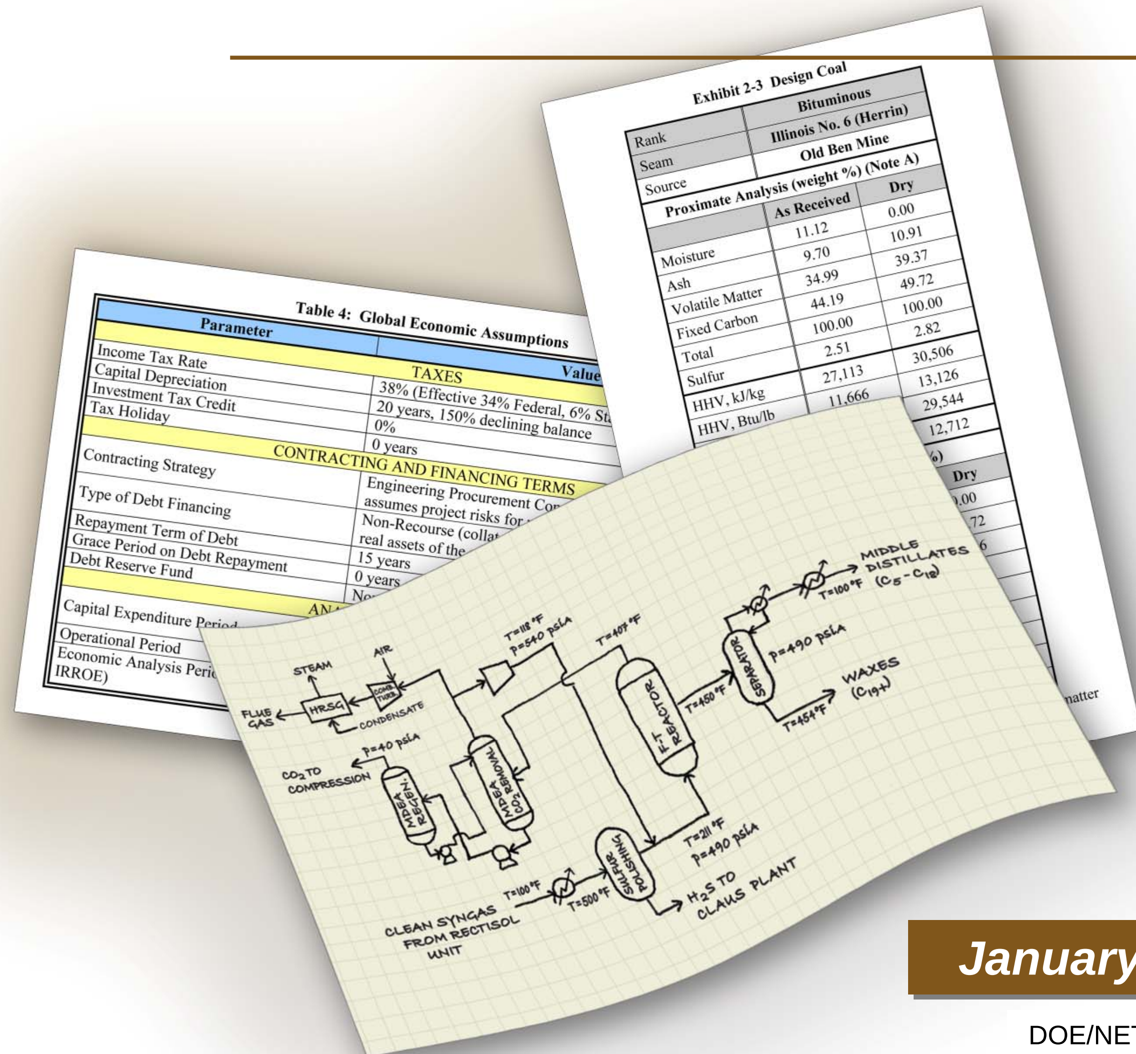
the ENERGY lab

QUALITY GUIDELINES FOR ENERGY SYSTEM STUDIES

Technology Learning Curve (FOAK to NOAK)



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1 Introduction

This paper summarizes costing methodologies employed by NETL for estimating future costs of mature commercial Nth-of-a-kind (NOAK) power plants from initial first-of-a-kind (FOAK) estimates for use in costing models and reports. Further, it defines the specific steps and factors which can be used in such estimation calculations. This methodology is based on major plant components for various technologies. Though these guidelines are tailored for power producing plants, they can also be applied to a variety of different revenue generating plants (e.g., coal to liquids, syngas generation, hydrogen, etc.).

As new technologies are developed and deployed, it is important that decision-makers have a reliable method of projecting future costs. History shows that subsequent installations will normally cost less than the first plant. Along with lower capital costs, efficiency and reliability will also tend to improve. When costs, efficiency, and reliability show little or no improvement from one plant to the next, the technology is considered mature.

1.1 Definition of Terms

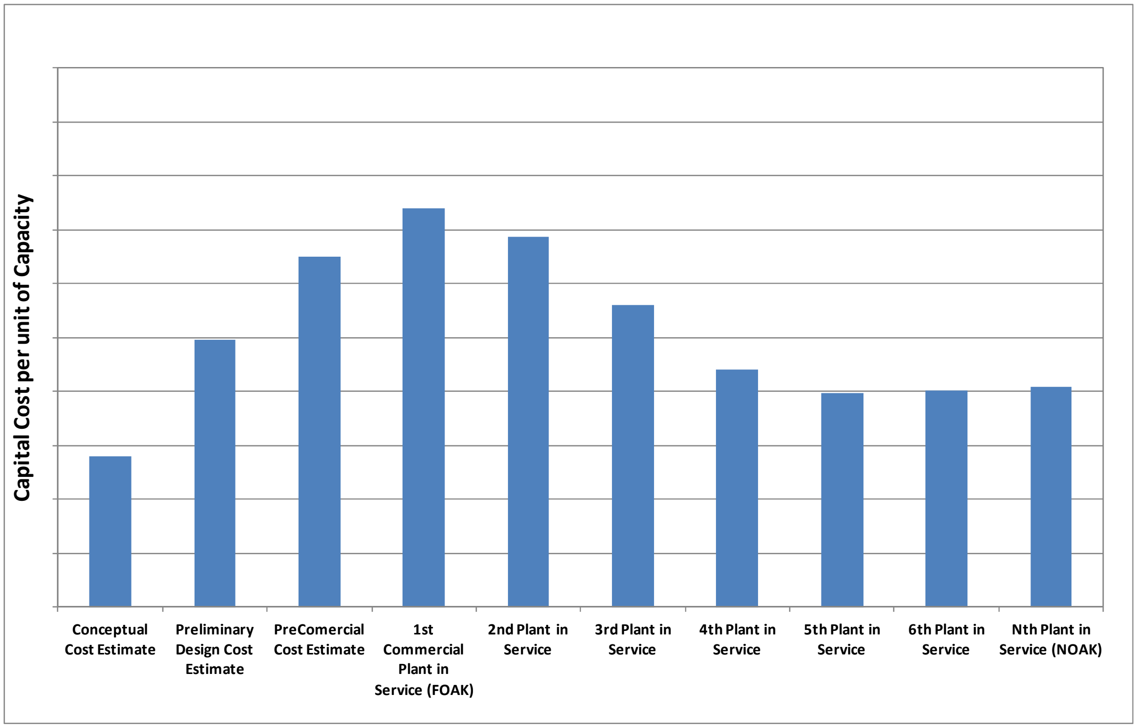
Care is needed in defining first-of-a-kind (FOAK) and Nth-of-a-kind plants (NOAK). For major new facilities, the number of installations is largely applicable to a specific supplier's technology. For example, although the gasification technologies are similar, it is unlikely that one vendor will share sufficient experience to benefit rivals. Therefore, the E-Gas IGCC system to be installed as part of the Excelsior project is a second-of-a-kind IGCC based on the Wabash project experience, since little or no benefit from other existing plants such as the Pinon Pine (KRW) project, Polk (GEE) project, Buggenum and Puertollano (Shell) projects is available to ConocoPhillips in sufficient detail.

Some projects are clearly FOAK based on a new technology. The transport gasifier to be demonstrated in Southern Company's CCPI project falls into this category. Projects that use Nth plant technology, but use large, new, critical subsystems should also be considered FOAK. An example of this would be if a gasification technology vendor achieves Nth plant status for IGCC systems and decides to use membrane technology for the ASU or a Posimetric® solids feed pump in the Nth plus one plant. Not only would these be new, but integration issues may occur and, as such, NOAK may not apply.

An additional issue to consider is that cost reductions do not always begin with the second plant. The methods to estimate Nth plant costs that are discussed below tacitly assume that the first plant operates reasonably well and that the main reason for higher FOAK plant costs is a conservative design. However, in some cases the FOAK plant experience leads to unpredictable problems and the realization that more components or more expensive components are needed. In these cases, the costs may actually increase for the first few plants. This is demonstrated by the data presented for SCR and FGD in Reference 1. When this situation occurs, the FOAK plant may need to be considered as the one where costs reach a maximum. Since these problems are unforeseen, it is impossible to know beforehand when costs will escalate in this manner.

The definition of the (NOAK) plant is somewhat arbitrary, although it is often taken as the fifth or higher plant. As stated above, it is essentially the plant when the benefits of experience become relatively minor. Furthermore, there is a point at which minimum plant cost is reached based on the costs of raw materials and components. It should be pointed out that even FOAK plants use mostly NOAK components (e.g. cryogenic ASUs in IGCC). The impact of time and experience on capital costs is illustrated in Exhibit 1-1.

Exhibit 1-1 Typical Impact of Experience on Power Plant Costs



1.2 Methodologies

Essentially there are two approaches to estimating future costs. The first is a traditional engineering-economic design approach based on engineering process models, databases containing previous and current vendor data, standardized factors and indices, and projections by experts in various fields regarding potential improvements in key process and economic parameters. The second is an equation based approach using mathematical learning or experience curves developed from historical data for similar technologies in similar systems. Both methodologies are described in the following sections.

2 Engineering-Economic Design Method

Costs often decline after a new technology is commercialized as improved versions are built. When the technology is well established and being produced by many vendors in competition with each other, the technology is referred to as "mature."

Actual capital and operating and maintenance (O&M) cost estimates for specific power generation process equipment and technologies are generated based on detail design parameters, engineering process models, databases containing previous and current vendor data, standardized factors and indices, and projections by experts in various fields regarding potential improvements in key process and economic parameters. Conceptual cost estimates used in techno-economic studies are typically factored from previous estimation data and are not as accurate as actual detailed estimates. Databases, indices, and conceptual estimating models are maintained as part of plant design bases of experience for similar equipment in power and process projects. The initial values are scaled and modified based on capacity, operating conditions, and application to generate final capital cost estimates for specific installations. Adjustment of costs for capacity and design conditions is a well-established technique and is highly accurate when properly done [2]. NOAK plant costs can be estimated from FOAK costs by applying the expected NOAK design parameter factors and indices along with sound engineering and estimating judgment.

Most techno-economic studies completed by NETL feature cost estimates carrying an accuracy of -15%/+30%, consistent with a "feasibility study" (AACE Class 4) level of design engineering applied to the various cases [3, 4, 5]. The reader is cautioned that the values generated for many techno-economic studies have been developed for the specific purpose of comparing the relative cost of differing technologies. They are not intended to represent a definitive point cost nor are they generally FOAK values.

Process and project contingencies are included in estimates to account for known unknown costs as well as those costs that are unforeseen due to a lack of complete project definition and engineering. Contingencies are added because experience has shown that such costs are likely, and expected, to be incurred even though they cannot be explicitly determined at the time the estimate is prepared. As technologies mature and estimates progress to more complete design levels, the contingencies are reduced [5].

Many factors can impact the cost of future technology installations even after the technology is commercially mature [6] and this approach takes them into account. Some of the factors are…

Market factors: If demand for a specific technology is high or there is a shortage of materials or manufacturing capacity, costs tend to increase for that technology or its components. If the demand is weak or supply is abundant, costs tend to fall. An "equilibrium" market condition exists in between these two extremes where small changes in demand do not impact costs significantly [6]. Competition, both foreign and domestic, also impacts costs.

Manufacturing factors: Costs for technology components manufactured in large facilities or at large production rates are usually lower than those for limited production versions. Modular components such as fuel cells, combustion turbines, and batteries, can be expected to be mass-produced [6].

Scaling factors: (Typically referred to as economy of scale) Larger equipment tends to cost less per unit of capacity when compared to smaller units. As technologies mature and installed capacity increases, the individual units tend to be larger [6].

Material price factors: Increases and decreases in costs and availability of raw materials and feedstocks used to manufacture equipment as well as operation and maintenance costs impact the overall costs for a technology or plant [6].

Inflation factors: Previous cost estimates can be updated to today's dollars by using cost indices such as Gross Domestic Product (GDP) [7] and Chemical Engineering's Plant Cost Index (CEPCI) [8] or other similar factors.

Location factors: Costs for land, labor, transportation, equipment installation, design, and construction (including contractor fees) vary significantly between locations [6]. Installation/construction costs are included in capital estimates and influenced by seismic zone, accessibility, excessive rock, piles, laydown space, etc. Design variations due to elevation, water availability, weather, seismic conditions, etc. also impact estimated cost projections [3].

Regulatory factors: Taxes, permitting requirements, licensing fees, and government incentives can impact capital cost estimates as well as operating and maintenance estimates. Current and potential regulation of air, water, and solid waste discharges also impact equipment selection and availability and, therefore, demand and final cost values [6].

Capital costs are dependent on the accuracy and completeness of designs. The most definitive of the estimate techniques are detailed, unit-cost, or activity-based cost estimates that use information down to the lowest level of detail available [9]. Conceptual/factored estimates are dependent on the accuracy of the original estimates. Many of these external factors change from plant to plant, regardless of the maturity level of the technologies. Care should be taken to insure the accuracy of any FOAK estimates and to include all applicable influences when projecting the values to NOAK installation cost values.

3 Learning Curve Method

The equation approach is based on using mathematical learning or experience curves developed from historical data for similar technologies in similar systems. Learning curves or experience curves are used to predict costs of manufactured products after some experience is gained in their production. They are also applicable to estimating plant costs for subsequent plants using the same technology. These curves are the standard methodology for projecting production costs or constant dollar capital costs based on the first unit or plant costs. While several attempts have been made to develop multi-factored curves, the most commonly used type of curve is based on the premise that some reduction in costs will take place each time the cumulative production is doubled [10, 11, 12, 13].

This is represented mathematically by:

$$\mathbf{Y=AX^{-b}} \qquad \mathbf{(1)}$$

Where Y = time or cost to produce X^{th} unit

A = time or cost to produce the of the first-of-a-kind unit

X = cumulative number of units, capacity, or ratio of capacities

b = learning rate exponent

The learning rate exponent is mathematically calculated by:

$$\mathbf{b = - \log(1\text{-}R) / \log(2)} \qquad \mathbf{(2)}$$

Where R = the learning rate defined as $(1 – 2^{-b})$

2^{-b} = the progress ratio

Note - learning rates and progress ratios are reported in literature (as fractions or percentages) or can be derived from historical data [13, 14].

Exhibit 3-1 graphically demonstrates the rate at which the benefits of experience decline for a number of different learning rates.

The value of R varies from industry to industry, company to company, and can vary from plant to plant within a company. Likewise this value will vary from technology to technology. Thus the learning rate for IGCC will differ from that of fuel cells and the learning rate for E-Gas will possibly differ from that of the GEE gasifier, although one would expect learning rates to be closer for similar technologies. The value assigned for R to a given technology can be based on the experience of estimators within the energy industry.

Complex systems such as power generation facilities consist of many technologies. Each of the technologies can be at a different maturity level. The results of a literature search conducted on power generation process technology cost estimation data has yielded two lists of learning rate recommendations shown in Exhibit 3-2 and Exhibit 3-3 [14, 15].

Exhibit 3-1 Learning Curves for Various Learning Rates

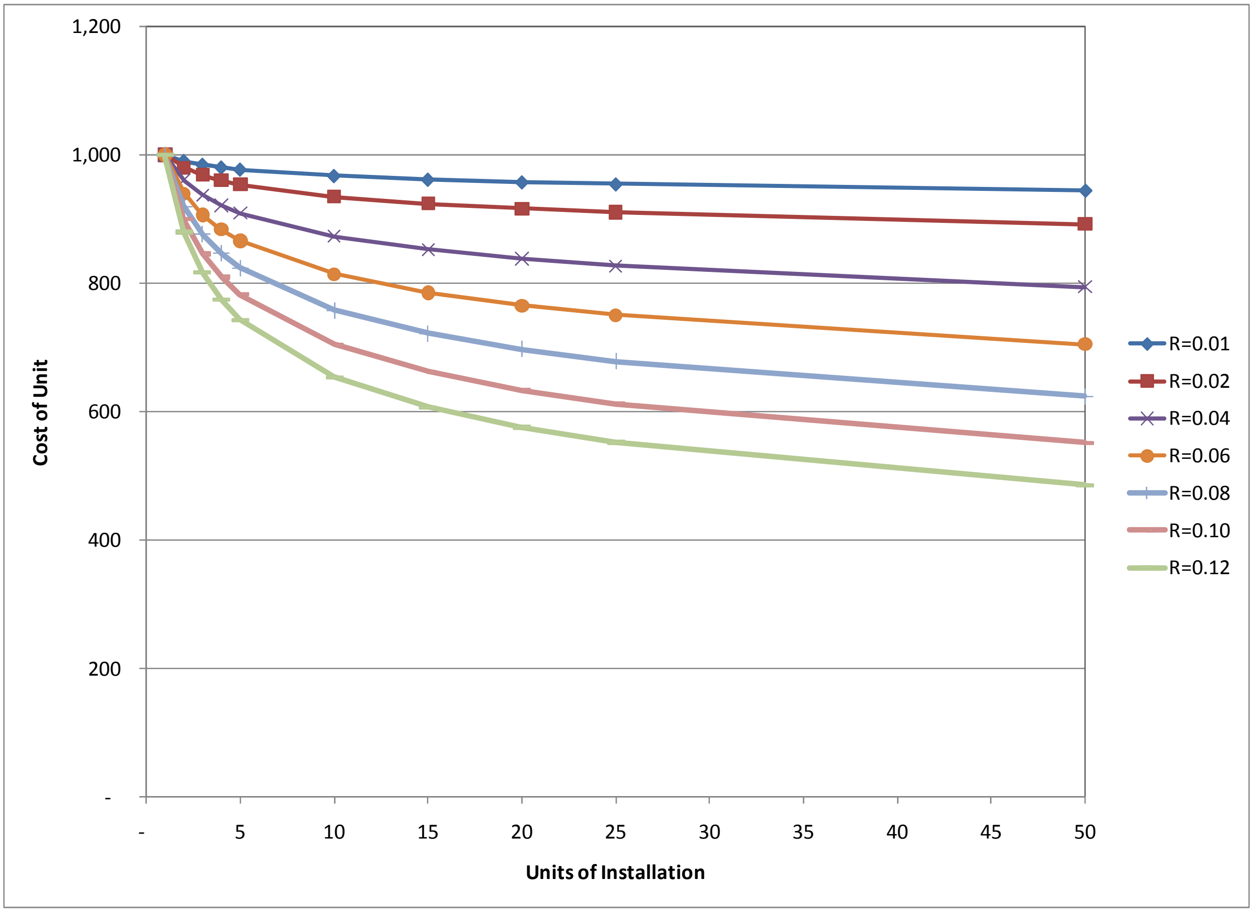


Exhibit 3-2 Typical R-values Versus Maturity Level

Level of Maturity	R - Value
Experimental (FOAK)	0.06
Promising, 2nd	0.05
Growing, 3rd & 4th	0.04
Proven, 5th to 8th	0.03
Successful, 9th to 16th	0.02
Mature, 17th & more	0.01

Exhibit 3-3 Recommended R-values for Various Technologies

Cost Category/Technology Type	R Value	Cost Category/Technology Type	R Value
Category 1		Category 5 (cont'd)	
Coal Delivery and Handling	0.01	CO_2 Capture, Recovery, & Compression	0.03
Category 2		CO_2 Transport & Sequestration	0.05
Coal Prep and Feed	0.01 - 0.04*	Fuel Cells	0.02 - 0.06**
Category 3		H_2 Production	0.02
Feed Water/Misc. BOP	0.01 – 0.05*	Direct Liquefaction Process	0.06**
Category 4	0.01 – 0.04	CH_4 From Hydrates	0.06**
Boiler Equipment & Aux.	0.01	Category 6	0.01 – 0.05
Gasifier Systems	0.04 - 0.06*	Advanced Comb. Turbines	0.04
Syngas Cooling	0.04	Syngas Comb. Turbines	0.05
Air Separation Units	0.03	Hydrogen Comb. Turbines	0.05
O_2 Membrane	--	N. G. Combustion Turbines	0.01
Category 5	0.02 – 0.05	Category 7	
Syngas Cleanup		Heat Recovery Systems	0.01
Acid Gas Removal	0.03	Category 8	0.01 - 0.04
Particulate Removal	0.03	Steam Turbines	0.01
Mercury Removal	0.03	Advanced Steam Turbines	0.04
HAPs Removal	--	Category 9	
Warm Gas Cleanup	0.03 – 0.04*	Cooling Towers/Systems	0.01
Sulfur Recovery	0.03	Category 10	
Flue Gas Cleanup	0.02 – 0.03	Ash/Slag/Spent Sorbent Handling	0.02
SO_2 Removal	0.02	Category 11	
NO_x Removal	0.02	Power Distribution System	0.01
Particulate Removal	0.02	Category 12	
Mercury Removal	0.03	Instruments & Controls	0.01
Haps Removal	--	Category 13	
Syngas Conversion	0.03 – 0.05	Site Preparation	0.01
Fischer Tropsch Synthesis	0.05	Category 14	
Methanol & Ethanol Production	0.03	Buildings & Structures	0.01
Methanation/SNG Production	--		

Estimating the N^{th} plant cost can be done by either applying the learning curve to major components or a plant-wide basis [13]. If it is done on a plant wide basis, the value selected for R should reflect the mix of mature and immature technologies and the anticipated learning rate for those immature technologies. Thus, a plant consisting largely of immature technologies would normally have a higher value for R than a plant with only a small portion of immature technologies. The difficulty in weighting the various R values for different components can be overcome by estimating each major subsection separately to arrive at a total cost for the N^{th} plant. The historical data that was analyzed represents past experience and provides some guidance in selecting R value ranges in the final methodology. For the technologies that are represented in typical power plants, the bulk of the learning rates are for technologies that are now NOAK.

This learning curve methodology is used extensively for applying currently available information to long term projections based on national and global generation capacities such as those made to study global energy costs for policy making decisions [16, 17, 18].

4 Learning Curve Example Calculations

The results of three example calculations using the learning curve method are presented in Exhibit 4-2, Exhibit 4-3, and Exhibit 4-4 for IGCC, super-critical PC, and NGCC plants with CO_2 capture. The base values were obtained from the DOE/NETL Bituminous Baseline Report [3]. Values from the IEA-GHG Report 2006/6 [13] were converted to 2007 dollars (shown in Exhibit 4-5) and included for comparison. The values for each plant type were estimated for the 5^{th} plant as well as 100,000 MWe of total installed capacity. The overall total plant costs (TPC) for each case are illustrated in Exhibit 4-1. The chart shows that while the starting capital costs from the Bituminous Baseline Report are significantly higher than those from the IEA-GHG Report, the R-Values and weighting method used in the examples generate very similar learning curves.

The results shown here are for example purposes only. The base estimate values used in these examples are conceptual only and not intended to be FOAK values. Use of this estimating procedure should be based on actual FOAK costs from historical data and not conceptual factored estimates.

Exhibit 4-1 Total Plant Costs using Learning Curve Methodology

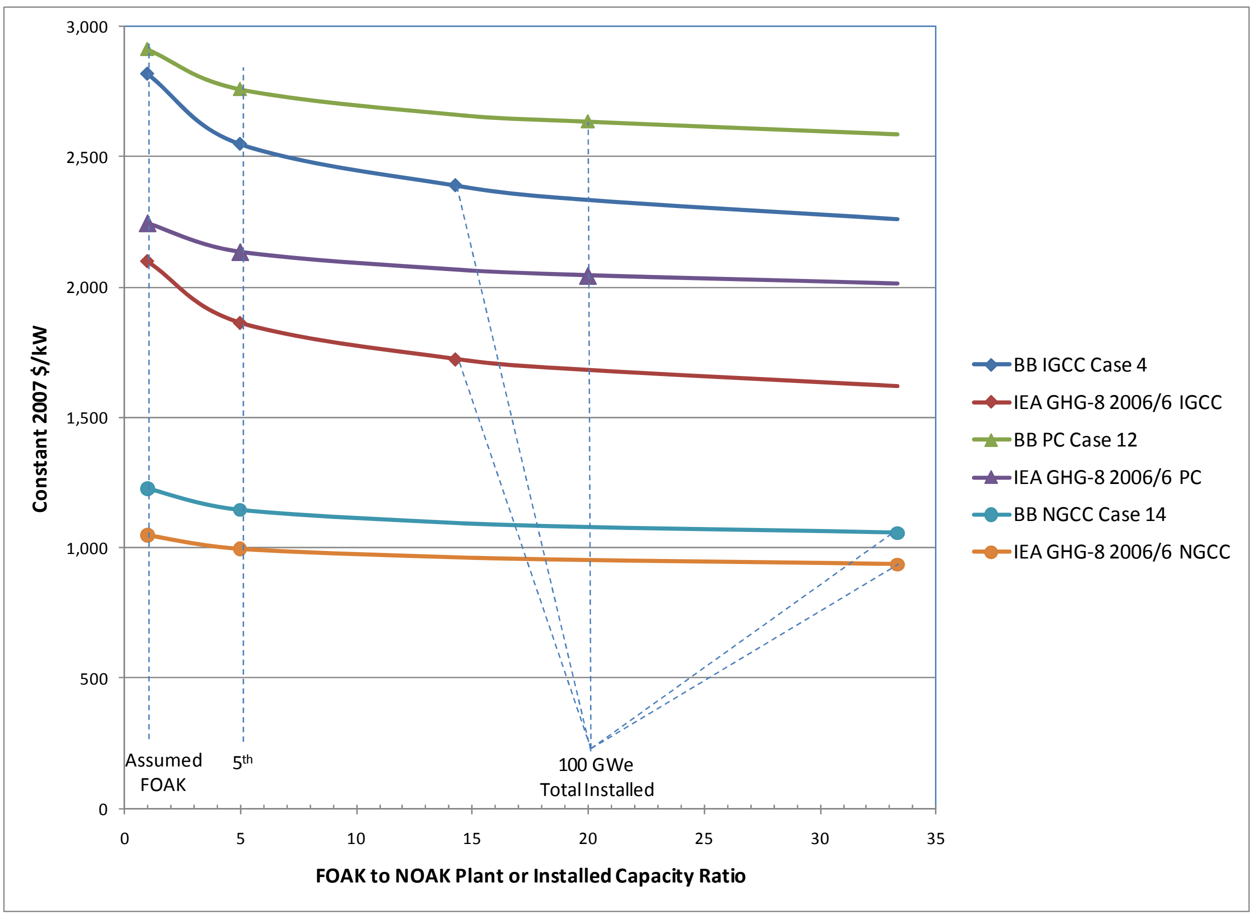


Exhibit 4-2 Learning Curve Methodology Applied to IGCC (BB Case 4)

System	Total Plant Cost, $x1000	Total Plant Cost, $/kW net (assumed FOAK)*	% Total Plant Cost	Progress Ratio, %	Learning Rate, R value	Exponent, -b	5th Plant Cost, $/kW net	100 GWe Installed Cost (based on 7 GWe initial installed), $/kW net
Coal Handling	36,529	71	2.5%	99%	0.01	-0.0145	69	68
Coal Prep & Feed System	56,648	110	3.9%	98%	0.02	-0.0291	105	102
Feedwater/Misc. BOP	37,858	74	2.6%	96%	0.04	-0.0589	67	63
Gasifier & Accessories	316,648	617	21.9%	94%	0.06	-0.0893	534	486
ASU/Oxidant Compression	224,461	437	15.5%	94%	0.06	-0.0893	379	345
Gas cleanup	256,707	500	17.7%	95%	0.05	-0.0740	444	411
CO_2 Removal/Compression	38,916	76	2.7%	97%	0.03	-0.0439	71	67
Combustion Turbine & Generator	132,015	257	9.1%	95%	0.05	-0.0740	228	211
HRSG/Ductwork/Stack	57,628	112	4.0%	99%	0.01	-0.0145	110	108
Steam Turbine/Generator	60,222	117	4.2%	96%	0.04	-0.0589	107	100
Cooling Water System	37,852	74	2.6%	99%	0.01	-0.0145	72	71
Ash/ Spent Sorbent Handling	37,536	73	2.6%	98%	0.02	-0.0291	70	68
Accessory Electric Plant	88,801	173	6.1%	99%	0.01	-0.0145	169	166
Instrumentation and Control	27,142	53	1.9%	99%	0.01	-0.0145	52	51
Site Preparation	19,796	39	1.4%	99%	0.01	-0.0145	38	37
Buildings and Structures	18,136	35	1.3%	99%	0.01	-0.0145	34	34
Total Cost	1,446,895	2,817	100%	96%	0.043	-0.0629	2,547	2,389
% Difference, FOAK to 5th, 100 GWe							9.6%	15.2%

***Costs presented in this table (2007$) are conceptual values used in example calculations only and do not represent actual FOAK data.**

Exhibit 4-3 Learning Curve Methodology Applied to a Supercritical PC Boiler (BB Case 12)

System	Total Plant Cost, $x1000	Total Plant Cost, $/kW net (assumed FOAK)*	% Total Plant Cost	Progress Ratio, %	Learning Rate, R value	Exponent, -b	5th Plant Cost, $/kW net	100 GWe Installed Cost (based on 5 GWe initial installed), $/kW net
Coal Handling	47,015	85	2.9%	99%	0.01	-0.0145	84	82
Coal Prep & Feed System	22,442	41	1.4%	96%	0.04	-0.0589	37	34
Feedwater/Misc. BOP	102,552	186	6.4%	95%	0.05	-0.0740	166	149
Boiler & Accessories	369,144	671	23.0%	99%	0.01	-0.0145	656	643
Gas cleanup	163,336	297	10.2%	97%	0.03	-0.0439	277	260
CO_2 Removal/Compression	468,782	852	29.3%	97%	0.03	-0.0439	794	747
Ductwork/Stack	37,526	68	2.3%	100%	0.00	0.0000	68	68
Steam Turbine/Generator	132,111	240	8.2%	96%	0.04	-0.0589	218	201
Cooling Water System	60,965	111	3.8%	99%	0.01	-0.0145	108	106
Ash Handling	15,108	27	0.9%	98%	0.02	-0.0291	26	25
Accessory Electric Plant	80,931	147	5.1%	99%	0.01	-0.0145	144	141
Instrumentation and Control	25,838	47	1.6%	99%	0.01	-0.0145	46	45
Site Preparation	15,717	29	1.0%	99%	0.01	-0.0145	28	27
Buildings and Structures	60,557	110	3.8%	99%	0.01	-0.0145	108	105
Total Cost	1,602,023	2,913	100%	98%	0.023	-0.0339	2,759	2,635
% Difference, FOAK to 5th, 100 GWe							5.3%	9.5%

***Costs presented in this table (2007$) are conceptual values used in example calculations only and do not represent actual FOAK data.**

Exhibit 4-4 Learning Curve Methodology Applied to NGCC (BB Case 14)

System	Total Plant Cost, $x1000	Total Plant Cost, $/kW net (assumed FOAK)*	% Total Plant Cost	Progress Ratio, %	Learning Rate, R value	Exponent, -b	5th Plant Cost, $/kW net	100 GWe Installed Cost (based on 3 GWe initial installed), $/kW net
Feedwater/Misc. BOP	46,312	98	8.0%	96%	0.04	-0.0589	89	80
CO_2 Removal/Compression	240,334	507	41.4%	97%	0.03	-0.0439	473	435
Combustion Turbine & Generator	97,490	206	16.8%	95%	0.05	-0.0740	183	159
HRSG/Ductwork/Stack	48,624	103	8.4%	99%	0.01	-0.0145	100	98
Steam Turbine/Generator	41,791	88	7.2%	96%	0.04	-0.0589	80	72
Cooling Water System	25,403	54	4.4%	99%	0.01	-0.0145	52	51
Accessory Electric Plant	45,888	97	7.9%	99%	0.01	-0.0145	95	92
Instrumentation and Control	15,318	32	2.6%	99%	0.01	-0.0145	32	31
Site Preparation	9,467	20	1.6%	99%	0.01	-0.0145	20	19
Buildings and Structures	10,075	21	1.7%	99%	0.01	-0.0145	21	20
Total Cost	580,701	1,226	100.0%	97%	0.030	-0.0433	1,144	1,056
% Difference, FOAK to 5^{th}, 100 GWe							6.7%	13.9%

***Costs presented in this table (2007$) are conceptual values used in example calculations only and do not represent actual FOAK data.**

Exhibit 4-5 Learning Curve Methodology Results in IEA-GHG 2006/6 Report

System	Starting Capacity GWe [13]	Total Plant Cost, $/kW net 2002$s (FOAK) [13]	Total Plant Cost, $/kW net 2007$s [7]	% Total Plant Cost	Progress Ratio, %	Learning Rate, R value	Exponent, -b	5th Plant Cost, $/kW net 2007$s	100 GWe Installed Cost, $/kW net 2007$s
IGCC Plant w/Capture	7	1,831	2,097	100.0%	95%	0.050	-0.0738	1,862	1,723
PC Plant w/Capture	5	1,962	2,246	100.0%	98%	0.021	-0.0314	2,136	2,045
NGCC Plant w/Capture	3	916	1,048	100.0%	98%	0.022	-0.0325	995	935

5 Summary

Based on the sample calculations, the proposed learning curve methodology generates reasonable predictions of NOAK plant costs from FOAK values when historical data is used to establish learning rates, capacity estimates, and FOAK cost values. The R-Values presented in this report can be used with the equations provided when detailed design information is insufficient for traditional cost estimation.

The following steps for applying the learning curve methodology are recommended and outlined in the IEA-GHG Report [13].

Step 1: Break each plant design into major technology sub-sections

Step 2: Estimate current plant costs and contributions of each sub-section

Step 3: Select an appropriate learning rate for each sub-section/component

Step 4: Estimate the current capacity of major plant components

Step 5: Set the start of learning (FOAK) and ending (NOAK) period

Step 6: Perform a sensitivity analysis

Final values can be adjusted using more traditional economic and engineering design indices if necessary.

Users are reminded that typical techno-economic cost estimates done at NETL are conceptual feasibility studies and not definitive cost values and therefore have an associated uncertainty that is larger than the magnitude of savings due to experience. NOAK plant cost projections will have the same level of uncertainty as the FOAK plant cost estimate and, in reality, will represent a mid-point of a band of possible costs.

While valid alternate methodologies exist, NETL has elected to use this learning curve method as the way of standardizing calculations for their studies.

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