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Toward improved cost guidelines for advanced low-carbon technologies

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Abstract

This paper presents a framework for estimating the future N^{th}-of-a-kind (NOAK) cost of advanced low-carbon technologies that are currently at early pre-commercial stages of development. It identifies two types of question that commonly motivate a cost analysis: "What If" questions about the hypothetical future cost of a technology that meets specified R&D goals or requirements; and "What Will" questions regarding the true expected cost of an advanced technology once it is mature and widely deployed. The latter type of question is the focus of this paper. It addresses shortcomings in the "bottom up" engineering-economic method current used to estimate NOAK costs. It describes a more rigorous hybrid costing method that combines a bottom-up analysis of the first-of-a-kind (FOAK) commercial cost of an advanced technology with an empirical model employing experience curves to project its future cost. Guidelines are presented for all phases of the analysis.

Keywords: Technology cost estimates; cost guidelines; advanced energy technologies; techno-economic assessments; first-of-a-kind (FOAK) plants; experience curves; N^{th}-of-a-kind (NOAK) plants; contingency cost factors; system contingency cost.

1. Background and Motivation

To assess the competitiveness and viability of an advanced low-carbon technology (such as a new carbon capture process or a novel power plant design), a common figure of merit is its expected future cost at commercial scale once it is mature and widely deployed—commonly referred to as the "N^{th}-of-a-kind" (NOAK) cost. Such estimates are commonly based on a detailed engineering-economic analysis using established costing methods for a proposed

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plant or process installation [1-3]. This "bottom up" costing method is intended for applications to near-term projects using currently available technology. In the context of NOAK cost estimates for advanced technologies, it is therefore appropriate only for addressing "What If" questions for a *hypothetical* future plant or process whose performance, operation, and cost characteristics are fully specified by the analyst (consistent with the premise of the analysis). However, this detailed costing method is not appropriate for addressing "What Will" questions regarding the future expected cost of a mature commercial technology that is currently at an early (pre-commercial) stage of development [3]. Rather, the only way to reliably estimate the actual expected cost of an N^{th} facility using a conventional engineering-economic analysis is by first having built and operated multiple plants (ideally, N–1) of a similar design.

Other recent papers and reports [4, 5] have elaborated on the shortcomings of current NOAK cost estimates and proposed an alternative hybrid costing method to address the class of "What Will" questions of interest to technology developers, researchers, and policy analysts. Prior work also elaborates on the proper use of bottom-up costing applied to hypothetical plant designs.

In this paper, we focus on the hybrid method of estimating the expected future cost of an advanced technology. That method combines two approaches to cost estimation. The first step is a conventional engineering-economic analysis of a commercial plant that would be built today using the advanced technology—typically the first-of-a-kind (FOAK) installation. Next, technology experience curve models are used to project the future cost trend as additional facilities are built and operated. In this formulation there is no explicit definition for the value of "*N*"; rather, a technology can be considered mature after a certain number of replications, or once its cost "levels off" as it is more widely deployed.

The guidance in this report is directed mainly at preliminary cost studies conducted in the early stages of a potential project for purposes of scoping and initial feasibility assessments (in contrast to the far more detailed and costly Front-End Engineering and Design studies used to support final investment decisions). Readers who are not familiar with cost study categories and engineering-economic methodology should review earlier work [1-3], which is foundational to the current effort.

2. FOAK Cost Estimates

Cost estimates for FOAK or early entry installations follow the same general methodology as for established technologies; however, many of the design, performance and cost factors differ significantly from those for mature technologies. In general, FOAK cost estimates are most appropriate for technologies that have advanced to at least large pilot plant or full-scale testing of the new process or system (e.g., TRL 6 or 7 on the Technology Readiness Level scale). Technologies at earlier stages of development are inherently much riskier, so FOAK cost estimates must also reflect the greater difficulty such projects would face in obtaining the financial and technical resources needed to actually undertake a commercial-scale project. The sections below highlight some of the areas where FOAK cost estimate differ from NOAK cost studies.

2.1. Plant and process design factors

All cost estimates begin with a specification of the plant and process designs and the battery limits of the project. For FOAK or other early-stage projects, the design is likely to include a greater degree of spare or redundant equipment, oversized vessels and other items that would not be found in mature plants, but which are incorporated in early designs to help ensure reliable operation and desired performance.

The most common applications of design margins are for essential equipment which must operate constantly, such as pumps, fans and valves. For advanced technologies being built at scale for the first time, or with little prior operating experience, there is a far greater need for spare (redundant) equipment to reduce risks. Thus, early-stage technologies commonly employ redundancy not only for essential items like pumps, values and fans, but also for major vessels that are critical to the operation of the new technology. For example, early deployments of flue gas desulfurization (FGD) systems at coal-fired power plants frequently employed a spare absorber train in addition to several operating trains, which has direct cost impacts. The need for redundancy should be determined based on a review of the factors that might cause a shutdown or poor performance of the new technology. Such factors would include the degree of scale-up, the duration and results of previous testing under a range of operating conditions, and the depth of technical understanding of the factors affecting the performance and reliability of the technology.

Similarly, FOAK designs for a full-scale plant may require the use of multiple vessels or trains due to limits on the size of available early-stage equipment. Thus, economies of scale (e.g., single large vessels or reactors) that are often assumed for future mature systems are often not available commercially for early installations, resulting in higher costs for FOAK projects.

Other factors affecting FOAK plant design that must be considered in preliminary cost estimates include:

- Use of non-standard materials in process design, with issues of cost and availability of suppliers and maintenance
- Compliance with applicable codes and standards which may require design alterations and due diligence review
- Incorporation of realistic operability measures, including controls, feedback and safety protections against forced outages and equipment malfunctions
- Incorporation of critical legal and contractual mechanisms needed to mitigate performance and schedule risks
- A hazard and operability analysis to provide evidence of safety and mitigation of design risks
- Inclusion of start-up, shut-down systems (often overlooked in FOAK designs).

2.2. Capital cost factors

Once the FOAK design is specified, the next step is to estimate its current capital cost based on the present state of technology development. Conceptually, this involves the same general procedure as for any other current project, i.e., first estimate the bare erected cost of the facility, then apply various indirect cost factors and contingency costs to calculate the total capital requirement [1, 2]. For FOAK plants, however, the magnitude of these cost elements is usually significantly higher than for plants employing conventional mature technologies.

2.2.1. Bare erected cost

In general, the BEC for a first-of-a-kind project will be significantly greater than for a mature technology or a plant assumed to meet R&D goals for performance and cost. Key contributors are more conservative designs to improve reliability (including oversized and redundant equipment), longer construction schedules, and the use of new components or materials that are not yet widely fabricated or produced in large quantities or sizes.

The most robust method of developing a BEC estimate for a commercial project is to employ an independent third-party entity with experience in estimating construction and sub-contractor costs for large-scale construction projects. If this option is not available or feasible (e.g., for a preliminary study), a BEC estimate for an advanced technology also can be developed based on guidance from cost estimation software, e.g. [6], as well as from widely-used textbooks and references on process equipment design and cost estimation, e.g. [7-9]. Where available, recent cost studies based on vendor quotes for similar processes or equipment also can be useful for bounding and scaling a BEC cost estimate. While the cost derived from any of these methods are subject to uncertainty, an effort to ensure that FOAK considerations are fully reflected in the BEC cost estimate is critical.

2.2.2. Process and project contingency costs

Capital cost estimates commonly include process and project contingency costs to estimate the miscellaneous additional costs not included in the BEC, but expected to occur as a project develops. The project contingency depends solely on the level of site-specific detail in the cost estimate. Thus, guidance on numerical values for FOAK plants is no different than for mature plants for a given level of site-specific detail [1, 2].

In contrast, the process contingency cost differs significantly for FOAK and mature technologies since it depends on the experience base and maturity of the technology at commercial scale. Table 1 shows the values recommended by the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (USDOE) for power plant processes at different levels of maturity [1, 2]. Approximate TRL values developed in this study also are shown.

Other recent studies recommend higher values of process contingencies that also depend on the level of engineering detail of the cost study [10]. Because contingency cost values for pre-commercial technologies have a wide range, professional and technical judgments are required to select an appropriate value based on the current status of technology development and an assessment of the risks in scaling up to a full-sized commercial FOAK facility.

Table 1. Process contingency cost guidelines [1, 2]

Current Technology Status	Indicative Equivalent TRL Value	Process Contingency Cost (% of associated process capital)
New concept with limited data	~3	40+
Concept with bench-scale data	~4	30-70
Small pilot plant data	5-6	20-35
Full-sized modules have been operated	7-8	5-20
Process is used commercially	9	0-10

2.2.3. System contingency cost

Advanced technologies often combine new or established process components in novel ways that have not yet been implemented at a commercial scale. In such cases, increased system complexity and novel integration schemes introduce new risks that tend to reduce the overall reliability of FOAK installations, even where only a single new process is integrated into a conventional plant for the first time. As a result, additional costs are likely to be incurred to achieve and maintain the design level of performance. These additional system-level costs can be significant but are not typically reflected in the process contingency cost factors described earlier.

To account for additional capital costs related to system integration and complexity, an additional contingency cost factor is introduced, called system contingency cost (Table 2). This factor is uniquely applicable to early installations of a new technology or system design, where integration-related problems first arise. The suggested cost factor is greatest for the first commercial installation, then decreases for subsequent projects. This assumes that any systems-related problems found at a FOAK installation results in design changes—and likely increases in BEC—to fix and finally eliminate the problem in subsequent replications. The suggested ranges have a lower bound of zero to accommodate an assumption of no additional cost risk from system integration.

Table 4-3. System contingency cost guidelines

Technology Status	System Contingency Cost (% total process capital for all newly integrated components)
First commercial-scale project (FOAK)	0 – 20
Second and third commercial projects	0 – 10
Fourth and fifth commercial projects	0 – 5
All subsequent commercial projects	0

A key distinction from the process contingency cost is that the system contingency cost factors depend only on the level of prior experience with the integrated system and not on the maturity of the individual technological components. Since this cost factor is not explicitly included in current costing methods [1-3], professional judgment is required to select a value appropriate for the context and degree of conservatism sought in the FOAK cost estimate. Ref. 5 provides additional discussion and documentation for this new capital cost factor.

2.2.4. Other FOAK cost factors

Two additional capital cost factors for FOAK technologies are highlighted. One is the escalation of capital costs during project planning and construction. While this is a standard factor in cost estimation, [1-3] FOAK projects are susceptible to greater escalation since project schedules are typically longer than for mature technologies. Thus, incorporation of a real cost escalation rate is recommended to provide additional confidence in the cost estimate. Numerical assumptions should be informed by current information on price trends for relevant materials and equipment.

The cost and schedule requirements for obtaining necessary permits to operate a FOAK facility is another factor often overlooked in the initial stages of advanced technology development. While this too is a standard element of bottom-up cost estimates [1-3], pre-commercial technologies typically require longer schedules and higher permitting costs than mature technologies. Adjustments to standard cost factors should again consider the status and degree of novelty of the advanced technology being analyzed.

2.3. Operating and maintenance cost factors

In general, estimated operating and maintenance (O&M) costs for FOAK projects are expected to be higher than for an equivalent mature installation. Thus, reporting and justification of assumptions is imperative for a credible cost estimate.

2.3.1. Variable O&M cost items

. Variable O&M (VOM) costs (which depend on the level of plant operation) are usually higher for FOAK facilities with advanced technologies that require supplies of new chemical reagents, sorbents or other materials that are not currently manufactured or available at commercial scales, and are therefore more costly. Uncertainty about the expected lifetime and replacement cost of a new sorbent or unique material can further increase O&M cost estimates as conservative assumptions are prudent for first-of-a-kind installations.

Where firm price quotes from material suppliers are not available, historical data on the price of analogous chemicals or materials, if applicable, may provide helpful guidance. Alternatively, a separate bottom-up analysis could be performed to estimate the cost of a facility to manufacture a new material or reagent currently produced in small quantities by the developer or intellectual property holder of the technology. The resulting cost per unit of product would provide rough guidance for an initial estimate.

All other VOM costs can be estimated following the standard cost guidelines cited earlier. Note, however, that the NETL methodology [2] treats the maintenance costs for planned and unplanned equipment outages as variable cost items. Prudence suggests that these costs also will be higher for FOAK installations due to the higher risk of unplanned outages.

2.3.2. Fixed O&M cost items

Fixed O&M (FOM) costs also are typically higher for FOAK facilities because of the likely needs for increased maintenance and operating labor, and engineering to support the operation of a new technology. Labor productivity assumptions also are critical, as project cost overruns for early-stage projects often have been attributed to lower productivity. Nominal values of these factors used by NETL and others for mature technologies should thus be increased for FOAK installations. Several other FOM cost items also are likely to be higher for FOAK facilities, including regulatory fees, accounting, legal and other professional services, tools/equipment, lease expenses, worker training, property taxes, and insurance. Here too, adjustments to standard guidelines for commercial technologies should be made based on the nature, complexity and current maturity of the advanced technology under study.

2.4. Financing and plant utilization factors

These factors are used together with capital and O&M costs to calculate the levelized cost of electricity (LCOE) for a power plant. Numerical values for FOAK plants differ from those for mature plants, reflecting the higher level of risk associated with early stage projects. This, in turn, increases the LCOE relative to mature plant assumptions.

2.4.1. Financial factors

The key financial factors relevant to FOAK projects are the weighted cost of capital and the expected lifetime (book life) of the project, which are the principal determinants of the fixed charge rate used to amortize the total capital requirement. Because FOAK projects lack prior operating experience, they typically incur a risk premium in the form of a higher cost of capital for project financing. Past NETL studies, for example, assumed a "high risk" weighted cost of capital that was 10% (0.7 percentage points) higher than the "low risk" (also called "commercial") cost of capital. Others, however, assume much larger differences (e.g., several percentage points) between high-risk and low-risk projects. In general, the magnitude of the risk premium will depend on the circumstances of the particular project and the risk profile of the FOAK technology.

Some FOAK projects also are planned to have a shorter operating life than a conventional new facility (especially retrofit projects). This results in a higher capital charge rate which further increases the estimated LCOE. Therefore, the assumed project lifetime should be carefully considered and reported in any FOAK cost study.

2.4.2. Plant utilization factor

The levelized capacity factor over the operating life of a facility is a critical determinant of its levelized cost of generating electricity (or other product). This parameter value for an FOAK plant is likely to differ significantly from prevailing assumptions for a hypothetical mature facility using the same technology. Two general factors contribute to this difference. One is the perspective or purpose of the cost analysis. The other is the technical readiness and reliability of the advanced technology being costed.

The "what will" perspective of a FOAK analysis requires that the most realistic capacity factor assumption be used for the advanced technology under study. This is in contrast to the assumption found in many "what if" analyses of hypothetical NOAK power plants based on assumptions that may or may not be achievable—including assumptions about lifetime capacity factor. Typically, such studies assume a bounding "best case" in which capacity factor over the life of the plant is equal to the plant availability (commonly 85% or more). Data for operating plants, however, show that actual historical values of capacity factor are much lower than availability levels (e.g., for U.S. power plants, the average capacity factor for coal-fired units from 2010 to 2019 ranged from 67% to 48%, while for natural gas combined cycle units it ranged from 44% to 57%) [11]. Thus, best-case capacity factor assumptions lead to unrealistically low estimates of LCOE.

It should also be kept in mind that new plants typically have lower utilization levels during the initial break-in period. This is especially important for FOAK facilities because of their characteristically slower ramp-up rates as bugs are ironed out over the initial years of operation. This longer break-in period has a significant impact on the levelized value of capacity factor due to the effect of discounting [3]. The choice of levelized capacity factor also should be based on a consideration of how the facility is expected to operate (e.g., baseload vs. cycling or peaking), along with the frequency and duration of planned outages. In general, the levelized capacity factor for FOAK cost estimates should be less than that of a similar commercial facility.

2.5. Toward a future mature plant

The FOAK capital cost, O&M cost and LCOE estimates discussed above provide the starting point for projecting the expected cost of a future mature plant once the advanced technology is successfully commercialized and adopted broadly. The next section of this paper outlines the guidance for these NOAK cost projections.

3. Cost projections using experience curves

In contrast to the detailed "bottom up" estimate of FOAK cost, the second component of the hybrid costing method employs a "top down" model based on historical experience curves to project the future cost of an FOAK plant built today. Figure 1 illustrates the use of the hybrid method for an ideal case where the first commercial project (with capacity C1) achieves all performance goals, and subsequently declines in cost with increasing experience (reflected by cumulative installed capacity). The analysis then reveals the capacity, C2, needed to match the lower cost of a commercial baseline technology, and the additional experience, C3, needed to achieve a still lower cost target or goal.

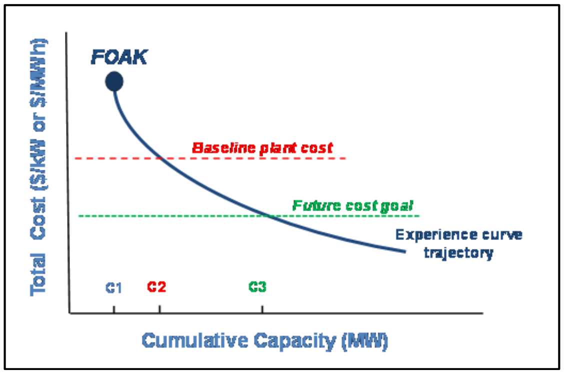

Fig. 1. Illustrative cost trajectory of an advanced technology as a function of cumulative installed capacity (experience)

Previous papers and reports have described the details of this approach, and the development of experience curves (also known as learning curves) for energy-related technologies [3, 4]. This paper briefly summarizes that guidance for advanced technology cost estimates. Further details can be found in Ref. 5.

3.1. Decomposing a plant into sub-sections

The first step in a plant-level analysis using experience curves is to decompose the overall facility into sub-sections whose costs are likely to change at different rates for a given increment of new plant capacity. Frequently, a new process or component (such as an advanced carbon capture system) is added to an otherwise mature plant design whose components are commercial and widely-used. In such cases, two sub-sections may suffice: the advanced technology and the balance of plant. In other cases, additional decomposition may be desired or helpful to refine the analysis. The principal criterion for the choice of sub-sections is their level of technological maturity and operating experience.

3.2. Estimating current sub-section costs

For power plants, the two cost measures needed for cost projections are the total capital requirement per unit of net plant capacity ($/kW) and the total annual O&M cost per unit of electricity generated ($/MWh). For other industrial processes, costs should be normalized on the capacity and unit cost of the major product. The total FOAK capital cost of the plant should then be decomposed to obtain the cost of each sub-section identified in Section 3.1. This is usually straightforward since the plant-level cost is built up from estimated components costs.

Similarly, fixed and variable O&M costs also should be allocated to plant sub-sections. Added requirements for electricity and steam produced within the plant are reflected in the net plant efficiency and plant-level purchases of fuels such as natural gas or coal. The total fuel energy requirement per unit of net plant output is then calculated and tracked to account for all in-plant energy use and improvements in overall plant efficiency as advanced technologies or other plant components mature.

3.3. Experience curve parameters

Experience curves are derived from historical cost trends and are most commonly expressed by the equation:

$$y = ax^{-b} \tag{1}$$

where, y = cost per unit for the x^{th} unit of plant capacity; a = cost for the first (initial) unit of capacity; x = ratio of cumulative to initial capacity of the technology; and, b = learning rate exponent.

Cumulative installed capacity is the most common independent variable for power plant technologies [4]. A key parameter is the learning rate, *LR*, defined as the fractional reduction in cost for a doubling of the initial capacity, and defined mathematically as:

$$LR = 1 - 2^{-b} \tag{2}$$

Values of *LR* are often reported as a percentage rather than a fraction. Given a reported value of the learning rate for a technology of interest, the exponent *b* value can then be calculated from Equation 1 and Equation 2 as:

$$b = -\log(1 - LR) / \log(2) \tag{3}$$

3.4. Selecting sub-section learning rates

Table A.1 of the Appendix summarizes the learning rates reported in recent studies and literature reviews for power plant and related chemical process technologies. In general, the experience curve literature is focused on capital costs; relatively few studies report learning rates for annual O&M costs.

The most straightforward choice of a learning rate for a sub-section is the reported value for a technology that is identical or similar to one under study. In some cases, prospective learning rates based on modeling studies also are available. In other cases, expert judgment may be required, drawing upon general characteristics of learning rate data for guidance. For example, the highest learning rates (e.g., 20–30 percent) are typically associated with smaller-scale technologies that are modular in nature and amenable to mass production (such as solar cells and panels). In contrast, learning rates are significantly lower for large-scale process systems and technologies that are typically field-erected and designed for a unique site or size (such as power plant boilers and pollution control systems).

Finally, the choice of a learning rate also may depend on the purpose of the analysis. For example, if the objective is to obtain a conservative or upper-bound estimate of future cost, then a low value of learning rate would be appropriate. In contrast, if the objective is to estimate a best-case or optimistic future cost, then a higher rate of learning would be used. In either case, care must be taken to avoid assumptions that lie outside the range of historical experience for similar types of technology if the result is to be credible.

3.5. Starting and end points for experience curve

For sub-sections involving advanced technologies, the most optimistic assumption is that the FOAK cost estimate for the advanced technology plant with capacity C1 (Fig. 1) is accurate and that the facility operates and performs as expected, with further cost reductions for all subsequent installations. A more conservative assumption, based on historical experience, is that several large-scale facilities must be designed, built and operated successfully before the estimated FOAK cost and performance for the advanced technology is actually achieved. In this case, learning does not begin until the installed capacity of the advanced technology has reached some minimum level, C_{min} (MW), a parameter of the analysis (see Ref. 5 for numerical examples).

At the far end of the cost curve, if the objective is to estimate the expected NOAK cost of the advanced technology a definition is needed for what constitutes the N^{th} plant. If defined in terms of cost reduction, analysis shows that for a mid-value learning rate of 15 percent, 20 replications (a little over four doublings of the initial capacity) is the point at which the cost falls to half its initial value based on Equation 1. Other assumptions for advanced and commercial technologies are discussed in Ref. 5.

Assumptions also are needed for the initial capacity of plant sub-sections with mature technologies that already are widely deployed. Here, simplifying assumptions can be made since there is little or no change in the cost of such technologies for relatively small increments of additional capacity. See Ref. 5 for examples and further discussion.

3.6. Projecting future costs

Once all sub-section learning rates and initial capacity values have been specified, Equation 1is used to project future sub-section costs, with the parameter, *b*, determined using Equation 3. Projections for O&M costs and plant efficiency improvements follow the same procedure where learning rate data are available. At the end point of the analysis (e.g., the defined N^{th} plant) the sub-section costs are then summed to obtain the total capital and O&M costs of the plant.

Similarly, a levelized cost of electricity can be calculated at any point in the projection by introducing appropriate values of levelized capacity factor and fixed charge factor, both of which tend to improve as technological risks decline with greater experience. Changes in these parameter values can be modelled simply as a step changes at particular points rather than as a continuous function.

4. Characterizing uncertainty

A final step that is strongly recommended in any cost projection is an uncertainty analysis for key results. While uncertainties are inherent in all cost estimates (e.g., -30% to +50% for a typical Class 4 cost estimate [2]), costs for NOAK technologies that are not yet commercial have significantly greater uncertainty and/or variability. The hybrid costing method introduces additional uncertainties associated with the learning curve analysis. Thus, it is important to recognize and characterize all major sources of uncertainty in advanced technology cost estimates in order to establish empirically-based bounds and expectations for future costs and cost reductions—a perspective critical for effective R&D planning and management of early-stage technologies. Details and illustrations of uncertainty analysis methods can be found in other recent reports [5, 18].

5. Conclusion

This paper has described an initial effort to improve current methods and guidance for cost studies of advanced low-carbon technologies still under development. Continuing efforts are needed to refine the models, databases and guidelines that support applications of the hybrid costing method outlined in this paper. Further applications of this method can begin to offer more complete and realistic assessments of the economic potential of advanced energy systems and priorities for R&D management.

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Appendix: Learning rate data

Table A.1. Learning rates for electric power generation and related technologies showing the percentage reduction in unit capital cost (or O&M cost) for each doubling of cumulative installed capacity or production, based on peer-reviewed literature sources

Energy Source and Technology*	N[a]	Learning Rate[b]				Source
		Range	Mean	Error[c]	Units	
Coal						
Pulverized coal plant (PC)	4	5.6% to 12%	8.3%		GW	[12]
FGD system	1		11%		GW	[13]
FGD system (O&M cost)	1		22%		GWh	[13]
SCR system	1		12%		GW	[13]
SCR system (O&M cost)	1		13%		GWh	[13]
Coal[b]	*1*	*–5% to 5%*	*0%*		*GW*	[14]
PC+CCS[b]	*2*	*1.1% to 9.9%*			*GW*	[12]
IGCC[b]	*2*	*2.5% to 16%*			*GW*	[12]
IGCC+CCS[b]	*2*	*2.5% to 20%*			*GW*	[12]
Natural Gas						
NGCC	5	–11% to 34%	14%		GW	[12]
Gas Turbine	11	10% to 22%	15%		GW	[12]
NGCC+CCS[b]	*1*	*2% to 7%*			*GW*	[12]
NGCC[b]	*1*	*2% to 15%*	6%		*GW*	[14]
Nuclear						
Nuclear plants	4	negative to 6%			GW	[12]
Nuclear plants	3	–49% to 22%	–44%		GW	[14]
Nuclear (business as usual)[b]	*1*	*–25% to 0%*	*–15%*		*GW*	[14]
Nuclear (optimal conditions)	*1*	*0% to 10%*	*5%*		*GW*	[14]
Biomass						
Power generation[d]	2	0% to 24%	11%		GW	[12]
Power generation	1		6%		GW	[14]
Hydroelectric						
Hydroelectric plant					GW	[12]
Fuel Cells						
FCEV fuel cell stacks			18.0%	1.7%	GWh	[15]
PEFC micro-CHP			19.3%	1.6%	No. units	[15]
Fuel cells (residential)		16% ± 2%[e]			GWh_{cap}	[16]
Hydrogen						
H_2 (alkaline electrolysis)			17.7%	5.3%	GW	[15]
H_2 (SMR)			27%		10^9 cu.ft.	[13]
H_2 (SMR) (O&M costs)			27%		10^9cu.ft.	[13]

Table A.1. (cont'd)

Wind						
Onshore	12	–11% to 32%	12%		GW	[12]
Onshore (1982-2016)			5.9%	1.3%	GW	[15]
Onshore (2009-2016)			24.5%	2.1%	GW	[15]
Offshore	2	5% to 19%	12%		GW	[12]
Offshore			10.3%	3.3%	GW	[15]
Onshore[b]		*–3% to 12%*	*5%*		GW	[15]
Offshore[b]		*–5% to 10%*	*3%*		GW	[15]
Solar						
PV system					GW	[12]
PV systems			18.6%	1.0%	GW	[15]
PV modules			21.4%	0.8%	GW	[15]
PV balance of system (BOS)			12.9%	1.7%	GW	[15]
CSP plants[b]	*5*	*3% to 12%*	*10.4%*		*GW*	[14]
PV (short-term)[b]	*1*	*15% to 23%*	*20%*		*GW*	[14]
PV (long-term)[b]	*1*	*8% to 17%*	*12%*		*GW*	[14]
CSP plants[b]	*1*	*3% to 12%*	*8%*		*GW*	[14]
Energy Storage						
Utility Li-ion storage			15.2%	3.7%	GWh_{cap}	[15]
Utility redox-flow storage			14.3%	6.1%	GWh_{cap}	[15]
Residential Li-ion storage			12.5%	3.0%	GWh_{cap}	[15]
BEV battery packs			15.2%	2.9%	GWh_{cap}	[15]
HEV battery packs			10.8%	0.6%	GWh_{cap}	[15]
Pumped hydro (utility)		–2% ± 8%[e]			GWh_{cap}	[16]
Other Technologies						
Heat pumps			10.0%		No. of units	[15]
LNG production			14%		Mt/yr	[13]
LNG prod. (O&M costs)			12%		Mt/yr	[13]
Oxygen production			10%		10^9 cu.ft.	[13]
Oxygen prod. (O&M costs)			5%		10^9 cu.ft.	[13]
Energy Efficiency						
Specific energy use (GJ/t)		12% to 29%			Mt product	[17]

[*]BEV= Battery electric vehicle; CCS= CO_2 capture and storage; CHP= Combined heat and power; CSP= Concentrated solar power; FCEV= Fuel cell electric vehicle; FGD= Flue gas desulfurization; HEV=Hybrid electric vehicle; IGCC= Integrated gasification combined cycle; LNG= Liquefied natural gas; NGCC= Natural gas combined cycle; PC= Pulverized coal; PEFC= Polymer electrolyte fuel cell; PV= Photovoltaic; SCR= Selective catalytic reduction; SMR= Steam methane reforming.

[a] Number of studies. Some studies report multiple values based on different datasets, regions, or assumptions

[b] LR values in italics reflect model estimates or other projections, not historical data; all values are reported as percentages rather than decimals; negative learning rates indicate increasing (rather than decreasing) costs; "Units" refers to x-axis quantity.

[c] Standard error equals square-root of the diagonal of the variance-covariance matrix

[d] Includes combined heat and power systems and biodigesters

[e] 95% standard error confidence interval.

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