

Low Wind Speed Technologies Annual Turbine Technology Update (ATTU) Process for Land-Based, Utility-Class Technologies

S. Schreck and A. Laxson

Technical Report
NREL/TP-500-37505
June 2005

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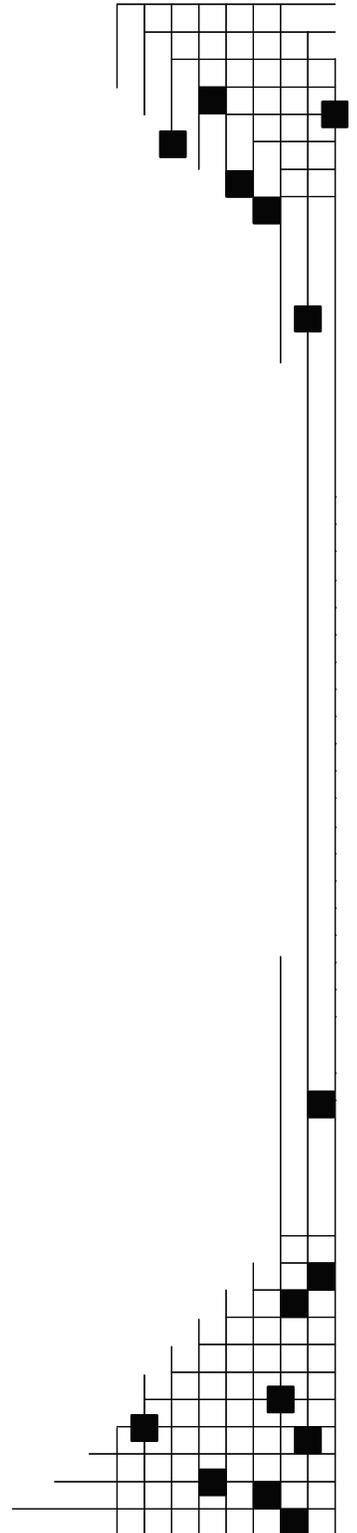


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S. Schreck and A. Laxson

Prepared under Task No. WER5.3200

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Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

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COST OF ENERGY GOAL AND TRENDS

The objective of the Low Wind Speed Technology Project is: “By 2012, reduce the cost of energy (COE) for large wind systems in Class 4 winds (average wind speed of 5.8 m/s at 10 m height) to 3 cents/kWh (in levelized 2002 dollars) for onshore systems.”

Thus far, competitive COE for wind energy has been achieved by focusing development on Class 6 sites (average wind speed of 6.7 m/s at 10 m height), and by taking advantage of the federal Production Tax Credit (1.8 cents/kWh in 2003 dollars). Even without the subsidy, current wind energy technology is such that, given favorable financing, wind generating plants at Class 6 sites can market electricity at prices of 4 cents/kWh or less.

However, as more and more sites have been developed, easily accessible Class 6 sites are becoming scarce. In addition, many remaining Class 6 sites are located in remote areas that lack ready access to transmission lines. Ultimately, the scarcity of accessible Class 6 sites may cause wind energy growth to plateau in the near future, unless improvements in technology can make lower wind speed sites more cost effective.

In contrast to Class 6 sites, Class 4 wind resources in the United States are abundant and lie relatively near transmission lines. However, at Class 4 sites, state-of-the-art turbines generate electricity at 4.3-5.0 cents/kWh, which is not competitive in present domestic energy markets. Equally important is the fact that without significant design improvements, current technology appears to be incapable of reducing COE in Class 4 resources to competitive levels. The Low Wind Speed Technologies Program is designed to overcome these limitations through research and development aimed at evolving cost competitive technologies specifically suited to Class 4 resource environments.

LWST PROGRAM TRACKING AND STRUCTURE

To guide wind technology development, the LWST Program quantitatively characterizes program direction and progress via two complementary analysis methodologies. The first is undertaken in response to Administration requirements dictating that federal programs be quantitatively monitored to ensure adequate return to the U.S. taxpayer. This directive is implemented through the Office of Management and Budget (OMB), and mandates that the LWST Program report an aggregate COE figure at the end of each fiscal year. An example of these data is shown in Figure 1, which appears as it might in FY08.

In this figure, program progress is represented by the descent of the plotted data with time toward the 2012 program goal of 3.0 cents/kWh. The 5.5 cents/kWh is referred to programmatically as the LWST Baseline. That figure was the Program’s best estimate, prior to performing detailed analyses, of what low wind speed technology cost at that time. Soon after, an analytical effort was begun to support annual tracking. The first step in that process was to develop a technology “reference turbine,” which now serves as the technology starting point for LWST analyses. The COE of that reference turbine was determined to be 4.8 cents/kWh, as shown in Figure 1.

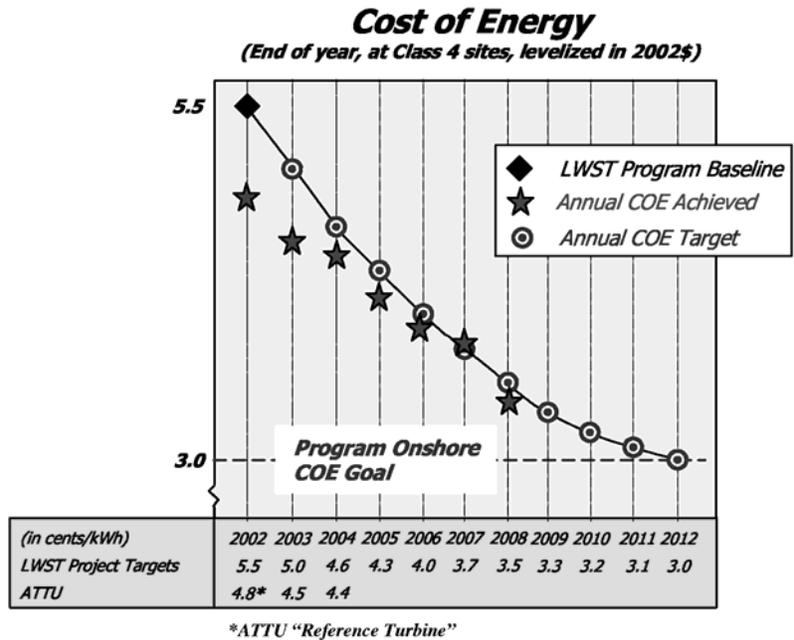


Figure 1. LWST aggregate COE vs. FY, showing possible realization for FY08.

The second analysis methodology is carried out as a guide to multi-year program planning and portfolio balancing. Reductions in aggregate program COE to the ultimate goal level will result from the combined impacts of incremental advances across several diverse technologies. Industry partners have identified a variety of technology and hardware approaches that could aid in reducing cost of energy, and have proposed to pursue these changes in their partnerships with DOE. The program refers to these as Technology Improvement Opportunities (TIOs). As the program tracks progress toward the COE goal, it also tracks progress against each of the TIOs, as shown in Figure 2.

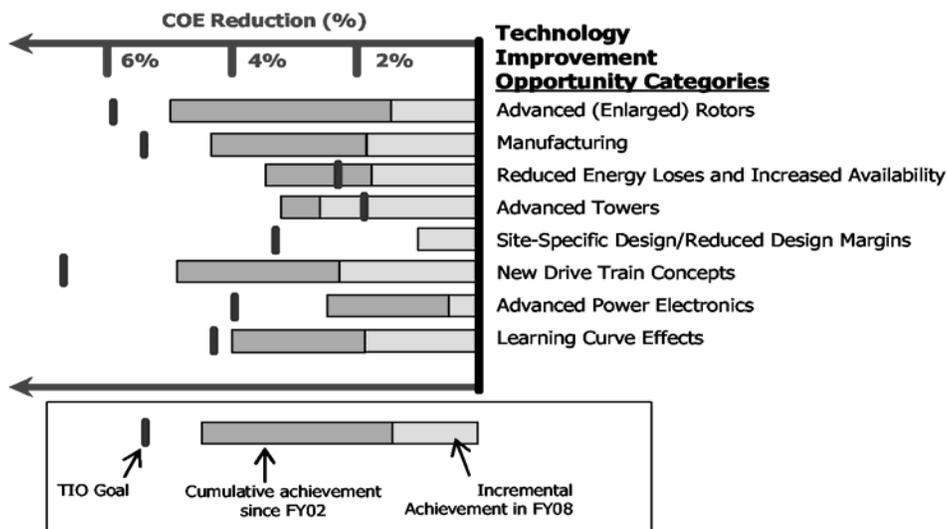


Figure 2. LWST COE reduction by TIO, showing possible realization for FY08.

Together, these two complementary analysis methodologies comprise a COE computation process termed the Annual Turbine Technology Update (ATTU). This ATTU process is documented below, as are the associated input and output data formats.

COST OF ENERGY COMPUTATION

Consistent with the DOE Wind Program, the ATTU employs a cash flow financial representation to calculate cost of energy on a levelized basis. The changes in TCC, BOS, LRC, O&M, and AEP are referenced to values for the LWST 2002 Reference Turbine (see below), and expressed as percent changes in response to LWST technology development accomplishments. The equation used in this method to compute COE, along with explanation of the variables, is shown as Equation 1. A detailed explanation of this methodology can be found in Appendix A.

$$\text{COE} = \frac{(\text{FCR} * (\text{TCC} + \text{BOS}))}{\text{AEP}} + \frac{(\text{LRC} + \text{O \& M})}{\text{AEP}} \quad (1)$$

- COE = Cost of Energy
- FCR = Fixed Charge Rate (11.85%, GenCo model)
- TCC = Turbine Capital Cost
- BOS = Balance of Station
- LRC = Levelized Replacement Cost
- O&M = Operations and Maintenance
- AEP = Annual Energy Production

LWST 2002 REFERENCE TURBINE

To enable consistent COE projections across several subcontracts involving diverse technologies over the life of the LWST program, a wind turbine configuration was chosen to function as a technology reference. The turbine configuration chosen is a composite turbine closely resembling the GE 1.5s Next Generation Turbine (NGT), which represents state-of-the-art wind technology for 2002. The Reference Turbine is rated at 1.5 MW, and has a three-blade, pitch controlled hub that sweeps a 70.5 m disk upwind of the tower. The GE 1.5 MW machine has been successfully commercialized, with well over 100 MW of rated capacity presently deployed, giving the Reference Turbine COE a high confidence level.

Because the GE NGT is a commercial machine, a substantial volume of pertinent engineering and cost documentation was not releasable outside the National Renewable Energy Laboratory. To complete the Reference Turbine data set for release to LWST subcontractors, surrogate data were extracted or derived from closely related work previously accomplished under the Wind Partnerships for Advanced Component

Technologies (WindPACT) Project. Once assembled, the complete reference data set was refined and validated using historical volume manufacturing and market data.



Figure 3. LWST 2002 Reference Turbine

SUBCONTRACTOR COE PROJECTIONS

Using the LWST 2002 Reference Turbine as the point of reference, subcontractors annually project component level COE improvements that have accrued from their work during the fiscal year. Resulting subcontractor COE projections are submitted to NREL in time to allow the annual ATTU to be completed before the end of the fiscal year.

Every LWST subcontractor documents their annual COE projections using the LWST COE Projection Form shown in Figure 4. The first column of Figure 4 lists several fundamental components of COE. These have been separated into categories corresponding to the five principal determinants of COE:

- 1) Turbine capital cost (TCC)
- 2) Balance of station (BOS)
- 3) Levelized replacement cost (LRC)
- 4) Operations and maintenance (O&M)
- 5) Annual energy production (AEP)

The second column contains component contributions to COE, expressed in U.S. dollars, corresponding to the LWST 2002 Reference Turbine. In the third column, subcontractors enter COE projections based on their LWST technology advances during the fiscal year. For many subcontracts, projected costs will differ from LWST reference costs for only a small subset of the listed components. This reflects the fact that most subcontracts are tightly focused to reduce costs in carefully defined turbine technology areas, as integral parts of a balanced program portfolio. The fourth column in Figure 4 documents component COE improvements, expressed as percent changes to the reference data in column two. Finally, column five contains summary percent cost improvements for each of the five principal COE determinants (TCC, BOS, LRC, O&M, and AEP).

LWST
Reference
Costs

Subcontractor
Projected
Costs

Component	Reference Component Costs \$1000	Projected Component Costs \$1000	Component Percent Improvement	Major Cost Element % Improvement
Rotor	248	248	0.0%	
Blades	148	148	0.0%	
Hub	64	64	0.0%	
Pitch mchsm & bearings	36	36	0.0%	
Drive train, nacelle	563	522	7.2%	
Low speed shaft	20	20	0.0%	
Bearings	12	12	0.0%	
Gearbox	151	151	0.0%	
Mech brake, HS cpling etc	3	3	0.0%	
Generator	98	98	0.0%	
Variable spd electronics	101	60	40.3%	
Yaw drive & bearing	12	12	0.0%	
Main frame	64	64	0.0%	
Electrical connections	60	60	0.0%	
Hydraulic system	7	7	0.0%	
Nacelle cover	36	36	0.0%	
Control, safety system	10	10	0.0%	
Tower	101	101	0.0%	
TURBINE CAPITAL COST (TCC)	922	881	4.4%	4.6%
Foundations	49	49	0.0%	
Transportation	51	51	0.0%	
Roads, civil works	79	79	0.0%	
Assembly & installation	51	51	0.0%	
Elect interf/c/connect	127	127	0.0%	
Permits, engineering	33	33	0.0%	
BALANCE OF STATION COST (BOS)	388	388	0.0%	0.0%
Initial capital cost (ICC)	1,310	1,269	3.1%	
Installed Cost per kW for 1.5 MW turbine (cost in \$)	873	846	3.1%	
Turbine Capital per kW sans BOS (cost in \$)	614	587	4.4%	
LEVELIZED REPLACEMENT COSTS (LRC)	15	15	0.0%	0.0%
O&M \$25/kW/Yr (O&M)	38	38	0.0%	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4576	4713	3.0%	3.0%
Net 8 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5637	5806	3.0%	3.0%
Fixed Charge Rate	11.85%			
COE at 5.8 m/s \$/kWh	0.0454	0.0431	5.2%	
COE at 8.4 m/s \$/kWh	0.0369	0.0350	5.2%	

Figure 4. LWST COE Projection Form containing typical subcontractor data.

From column five of each subcontractor’s LWST COE Projection Form, values for the five principal COE determinants (TCC, BOS, LRC, O&M, and AEP) are extracted and entered into a separate ATTU Subcontractor Data Input Worksheet, an example of which is shown in Appendix B, in Figures B1a and B1b. These five data elements are entered into the spreadsheet in the locations identified as “Subcontractor COE Projection Entry”.

TIO ALLOCATIONS

Examination of the LWST COE Projection Form in Figure 4 shows that COE projection data are acquired from subcontractors in a format consistent with general turbine structure and function. This format is beneficial in that consistency with turbine structure and function provides a context within which to understand the individual data elements, thus minimizing ambiguity in subcontractor data submission.

However, the ATTU must quantify the impact of LWST programmatic composition and process. Thus, after assimilation of subcontractor COE projection data, these projections are allocated across the LWST TIO categories, which were introduced in conjunction with Figure 2. This allocation requires understanding of both turbine configuration/operation as well as LWST program composition/process, and is performed by NREL and Sandia Subcontract Technical Monitors.

TIO allocation values are entered into a separate ATTU Subcontractor Data Input Worksheet for each subcontract. An example of this worksheet is shown in Appendix B, in Figures B1a and B1b. TIO allocation data elements are entered into the spreadsheet in the locations identified as “TIO Allocation Entry”.

TIO allocation is shown schematically in Figure 5. This figure depicts various modes in which subcontractor COE projections could be allocated to LWST TIO categories. The converging arrows represent aggregation, where subcontractor TCC and BOS improvements are combined into an improvement in LWST TIO 2. Alternatively, the diverging arrows represent apportionment of subcontractor O&M benefits between TIO 4 and TIO 5. In some cases, the COE impact projected by the subcontractor could transfer directly to another LWST TIO, as shown by the single arrow between LRC and TIO 6.

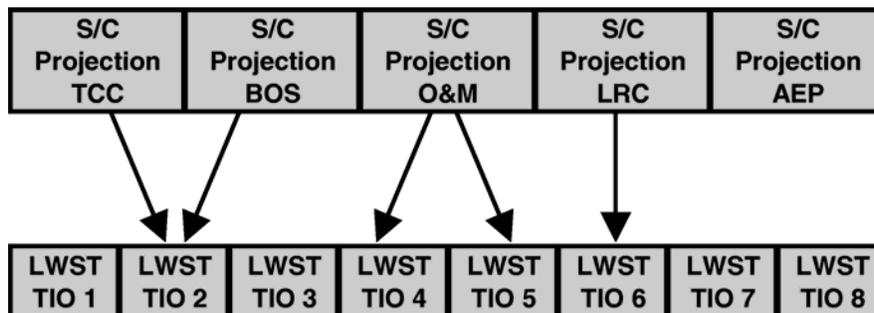


Figure 5. Schematic allocation of subcontractor COE projections to LWST TIOs.

SUBCONTRACT WORK PROGRESS AND TECHNOLOGY MATURITY WEIGHTS

Each LWST subcontractor’s COE projection represents the COE that the subcontractor estimates could be achieved, assuming their subcontract were to be completed and the results of their subcontract work were to be commercialized across 100 MW of wind generating capacity. Thus, in computing the ATTU for each fiscal year, weightings are applied which quantify subcontract completion and the commercialization readiness, or technology maturity, of the work at subcontract completion.

The first weighting factor corresponds to the percentage of subcontract work completed. This percentage is arrived at by first identifying significant phases in the subcontract work plan, as shown for the example project documented in Figure 6. Then, incremental completion percentages are assigned to these phases, depending upon the magnitude of effort required to complete each phase. Major work phases like detailed design, fabrication, and testing can be expected to comprise a major percentage of the total effort.

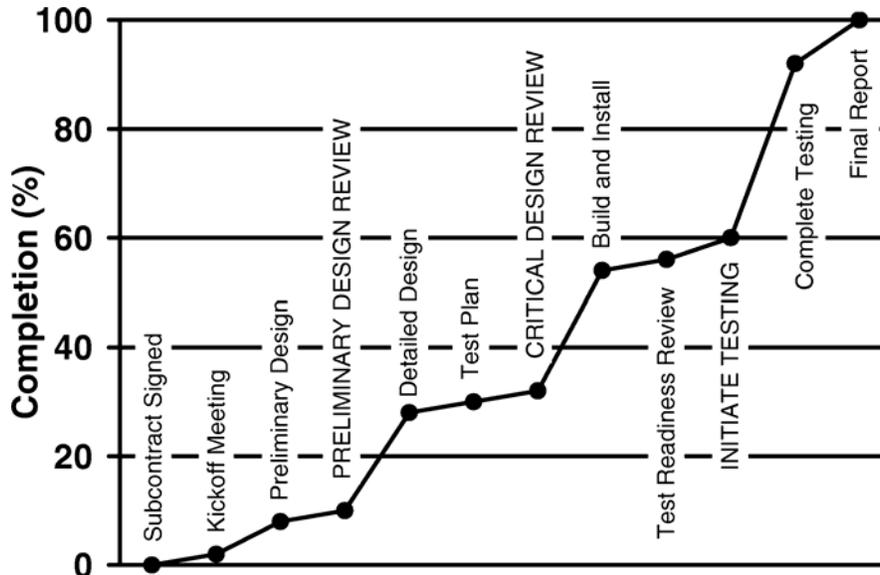


Figure 6. Graph of typical subcontract percent completion weights. Stage gate events labeled in capital letters.

At the inception of each subcontract, NREL and Sandia Subcontract Technical Monitors consult the Statement of Work to identify significant work phases for the subcontract. These are entered into an ATTU Subcontractor Data Input Worksheet for the subcontract, at the location marked “Subcontractor Work Progress Entry” in Figure B1b of Appendix B. During the subcontract performance period, Technical Monitors ascertain work progress using status reports submitted periodically by the subcontractor. Completion of work phases are entered into the spreadsheet by replacing “0” with “1”, again in the area marked “Subcontractor Work Progress Entry” in Figure B1b of Appendix B. Immediately to the right of this area, the quantity designated “Total % Complete” represents the completion weighting factor used in computing the ATTU.

The second weighting factor quantifies the technology maturity of the subcontract types encompassed by LWST, as shown in Figure 7. While commercialization and deployment activities are not funded under LWST, the program is structured to facilitate these ultimate goals. Thus, a technology maturity weight of 100 percent is reserved for LWST components or systems that have been successfully commercialized and deployed across at least 100 MW of wind generating capacity. In consistent fashion, the three types of LWST subcontract are assigned technology maturity weights of less than 100 percent, depending on the goal of the subcontract.

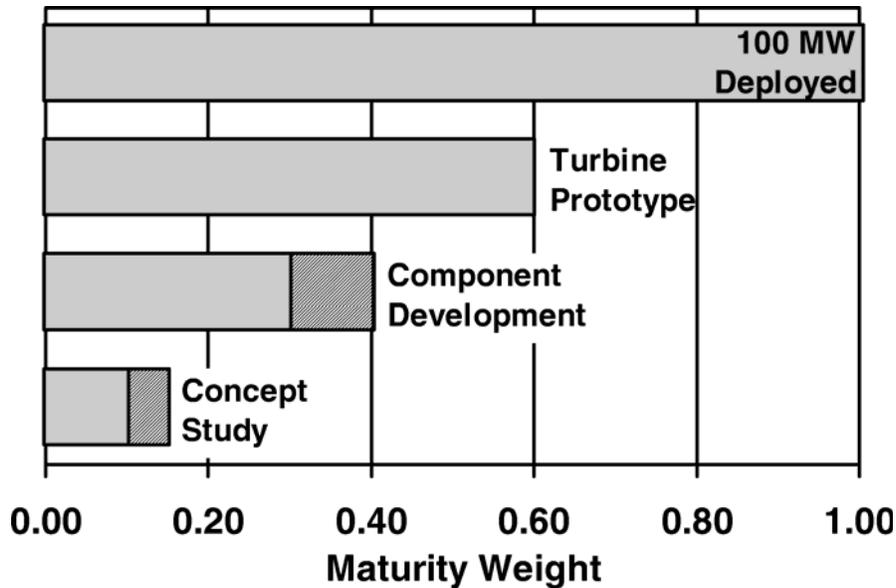


Figure 7. Technology maturity weights for various LWST subcontract types.

The first type of subcontract is for concept design studies. Concept studies offer an industry partner an opportunity to determine the probable value of a particular concept by performing a paper analysis before undertaking detailed design and fabrication. These small scale studies involve no cost sharing, keeping the results in the public domain. A technology maturity weight of 15 percent is assigned to concept studies that include fabrication or testing, while 10 percent is given to those culminating in a paper study.

The second type of subcontract is a cost-shared component development project. In this type of project, the industry partner completes detailed design and testing of an advanced prototype component or subsystem. Component development subcontracts that can be readily employed in a retrofit or otherwise easily integrated into existing machines are assigned a technology maturity weight of 40 percent. Component developments aimed at producing more integral components of future machines, such as drive trains, are given a maturity weight of 30 percent.

The third type of subcontract calls for the cost-shared detailed design, fabrication and field test of an advanced prototype turbine. These turbines will be tested in field environments to demonstrate the likelihood of achieving the LWST goal. These subcontracts are assigned a technology maturity weight of 60 percent.

SUBCONTRACT WEIGHTED TIO IMPACT

For each LWST subcontract, the four parameter sets explained previously and listed below are entered into a separate Subcontractor Data Input Worksheet (see Appendix B):

- Subcontractor COE Projections
- TIO Allocations
- Subcontractor Work Progress
- Subcontract Technology Maturity Weight

Entering these quantities into the worksheet yields Weighted TIO Impact data in the area indicated on the Subcontractor Data Input Worksheet in Figure B1a, of Appendix B. These Weighted TIO Impact data represent improvements to TCC, BOS, LRC, O&M, and AEP due to impacts from the TIO categories next to which the output data are listed. If a subcontract was not intended to impact a given COE component via a given TIO, then the cell at the intersection of that COE component column and that TIO category row will be blank. A cell containing a value of 0.00 indicates that the subcontract was intended to impact the associated COE component and TIO category, but did not do so during the fiscal year. Consistent with other COE data, the Weighted TIO Impact data are expressed as percent changes referenced to COE for the LWST 2002 Reference Turbine.

AGGREGATION OF SUBCONTRACT DATA

To this point in the ATTU process, data have been entered and results obtained for each individual subcontract. Further processing is required to obtain program-wide COE impact data aggregated by LWST TIO (for portfolio assessment), and aggregated as a unitary value for the LWST Program (for reporting up through DOE and OMB).

The first part of the aggregation process consists of obtaining program-wide COE impact data broken out according to the five COE components (TCC, BOS, LRC, O&M, and AEP) and the eight LWST TIO categories. Data in this format are contained in the Weighted TIO Impact area of the ATTU subcontractor input worksheet (example in Figure B1, of Appendix B). Here, the COE components correspond to columns and the TIO categories to rows.

Each cell in this spreadsheet area, corresponding to one COE component impacted by one TIO category, is aggregated across all such spreadsheets, with each spreadsheet corresponding to an active LWST subcontract. Aggregation consists of averaging the values contained in all occupied cells, and ignoring vacant cells. This process is repeated sequentially for each combination of COE component and TIO category, until all cells have been similarly aggregated. Figure 8 contains an example of COE impact data aggregated by TIO, to be used in an advisory capacity for LWST portfolio evaluation and balancing. These data are expressed as percent changes referenced to the LWST Reference Turbine data.

The second part of the aggregation process produces a single value of COE improvement for the overall LWST Program. This is accomplished using data like those contained in Figure 8, in conjunction with LWST Reference Turbine data and Equation 1. This COE improvement value is expressed in terms of cents/kWh.

LWST Annual Technology Update		Cumulative S/C Improvements From Baseline				
2004		TCC	LRC	O&M	BOS	AEP
1	Advanced Enlarged Rotor Designs	0.73%	-0.75%	-1.00%	0.22%	6.87%
1a	Advanced Materials	0.00%	0.00%	0.00%	0.00%	0.00%
1b	Changed Improved Structures	-0.54%	0.00%	0.00%	0.22%	0.39%
1c	Active Controls	1.27%	-0.75%	-1.00%	0.00%	6.48%
1d	Passive Controls	0.00%	0.00%	0.00%	0.00%	0.00%
1e	Higher tip Speed ratios/lower acoustics	0.00%	0.00%	0.00%	0.00%	0.00%
2	Manufacturing	0.00%	0.00%	0.00%	0.00%	0.00%
2a	Reduced Cost through Manufacturing Methods	0.00%	0.00%	0.00%	0.00%	0.00%
2b	Reduce Cost through lower margins	0.00%	0.00%	0.00%	0.00%	0.00%
2c	Reduce manufacturing markups	0.00%	0.00%	0.00%	0.00%	0.00%
3	Reduced Energy Losses and Increased Availability	-0.18%	0.00%	0.00%	0.07%	0.13%
3a	Health Monitoring-SCADA	0.00%	0.00%	0.00%	0.00%	0.00%
3b	Bladed Soiling Mitigation	0.00%	0.00%	0.00%	0.00%	0.00%
3c	Extended Scheduled Maintenance	-0.18%	0.00%	0.00%	0.07%	0.13%
4	Advanced Tower Concepts	-0.40%	0.00%	0.00%	0.07%	0.13%
4a	New Materials	0.00%	0.00%	0.00%	0.00%	0.00%
4b	Innovative Structural Approaches	-0.22%	0.00%	0.00%	0.00%	0.00%
4c	Advanced Foundations	0.00%	0.00%	0.00%	0.00%	0.00%
4d	Self Erection	-0.18%	0.00%	0.00%	0.07%	0.13%
5	Site Specific Design - Reducing Design Margins	0.00%	0.00%	0.00%	0.00%	0.00%
5a	Improved Definition of Site Characteristics	0.00%	0.00%	0.00%	0.00%	0.00%
5b	Design Load Tailoring	0.00%	0.00%	0.00%	0.00%	0.00%
5c	Micrositing	0.00%	0.00%	0.00%	0.00%	0.00%
5d	Favorable Wind Speed Distributions and Shear	0.00%	0.00%	0.00%	0.00%	0.00%
6	New Drive Train Concepts	-1.25%	0.00%	-3.00%	-0.21%	0.50%
6a	PM Generators	-0.61%	0.00%	-1.50%	-0.24%	0.20%
6b	Innovative Mechanical Drives	-0.65%	0.00%	-1.50%	0.03%	0.30%
7	Advanced Power Electronics	-0.20%	-6.00%	-6.00%	0.05%	0.13%
7a	Incorporation of Improved PE Components	-0.07%	0.00%	0.00%	0.01%	0.00%
7b	Advanced Circuit Topology	-0.13%	-6.00%	-6.00%	0.04%	0.13%
8	Learning Curve Effects	0.00%	0.00%	0.00%	0.00%	0.00%
	Total	-1.30%	-6.75%	-10.00%	0.21%	7.76%

Figure 8. Program-wide COE impact data aggregated by LWST TIO.

RECAPITULATION OF PROCESS

The ATTU process begins with subcontractor COE projections (Figure 9, block 1 in top row), computed as percentages with respect to the LWST Reference and submitted to NREL and Sandia Subcontract Technical Monitors on an annual basis. To minimize ambiguity in data submission, subcontractor COE projections are formatted consistent with wind turbine structure and function. Technical Monitors then allocate these data across the LWST TIO categories (Figure 9, block 2 in top row), consistent with LWST programmatic composition and process. Subsequently, two weighting factors are applied for each subcontract (Figure 9, blocks 3 and 4 in top row). The first quantifies subcontractor progress, expressed as percent completion, toward meeting the goals

established for the subcontract. The second accounts for technology maturity and commercialization readiness, assuming the subcontract has been completed.

To this point in the ATTU process, calculations are carried out separately for each individual subcontract. Subsequent stages of the process aggregate individual subcontract data in two consecutive stages. The first stage (Σ_1 in Figure 9) arrives at program-wide COE impact data, expressed as percent improvement, subdivided consistent with the five COE components (TCC, BOS, LRC, O&M, and AEP) and the eight LWST TIO categories. Using the data produced in the first stage, the second aggregation stage (Σ_2 in Figure 9) yields a unitary COE improvement value for the LWST Program, expressed in cents/kWh.

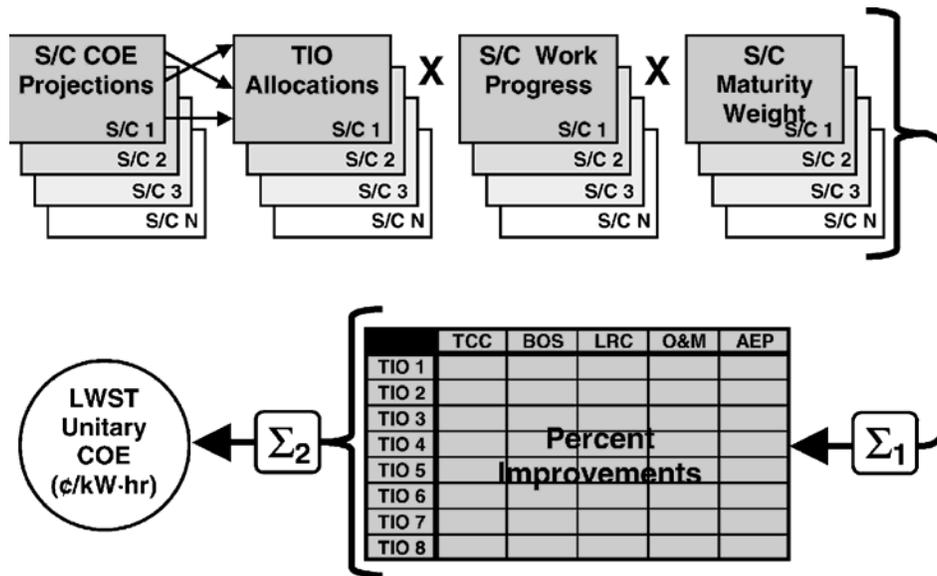


Figure 9. Summary of the ATTU process. Blocks containing Σ_1 and Σ_2 represent first and second parts of aggregation.

CONCLUSION

The Low Wind Speed Technologies Program comprises a diverse, balanced portfolio of industry-government partnerships structured to achieve ambitious cost of energy reduction goals. The Annual Turbine Technology Update has been developed to quantify performance-based progress toward these goals, in response to OMB reporting requirements and to meet internal DOE program needs for advisory data.

The ATTU process documented herein successfully balances several crucial, though conflicting requirements. Process inputs recapitulate turbine structure and operation, and are thus receptive to industry partner performance projections. Simultaneously, the ATTU translates these inputs to LWST programmatic composition and process, responding to crucial high level department and administration directives.

The methodology at the heart of the ATTU is simple, rendering it accessible for validation purposes and reliable in routine use. These same attributes also yield visibility and intelligibility for oversight and audit, thereby conferring credibility and defensibility. In addition, the ATTU methodology is inherently scalable, enabling it to accommodate the multiple subcontracts currently present in the diverse LWST portfolio, and to be readily expanded in the future as the LWST program continues to grow. Finally, all of these qualities also enable the ATTU to be updated on an annual basis, to reflect continual, performance-based progress toward LWST COE reduction objectives.

APPENDIX A

Cost of Energy Computation

This attachment describes the assumptions and methods that shall be used to define and support the primary figure-of-merit for advanced wind turbines developed under the DOE/NREL Low Wind Speed Technology project. The primary figure-of-merit, Cost of Energy (COE), is calculated using assumed wind conditions at two "Reference Sites" and economic parameters associated with a hypothetical Generation Company (GenCo) project utilizing corporate (balance sheet) financing. The calculation method presented below uses formulas to approximate the results of a detailed pro forma cash flow model used for commercial projects. NREL's Financial Analysis Tool for Electric Energy Projects (FATE2-P) was used to model a hypothetical GenCo project. In an attempt to standardize COE estimates, typical values for financial parameters (such as cost of capital and inflation rate) and fixed costs (such as insurance, property taxes and land lease) were chosen. These typical values reflect market conditions as of October 2001. The simplified calculation method presented herein provides a means to evaluate design alternatives on a comparative basis and develop data for NREL's wind program assessments. However, the method is not a reliable estimate of energy costs for planned or actual wind power plants.

Assumptions

The following assumptions shall be used to calculate the COE for two Reference Sites.

- Reference Site #1 (Class 4): representative of the Great Plains of the United States
 - 5.8 m/s annual average wind speed at a height of 10 m, Rayleigh distribution, vertical wind-shear exponent = 0.143
- Reference Site #2 (Class 6): representative of mountain ridge lines
 - 6.7 m/s annual average wind speed at a height of 10 m, Rayleigh distribution, vertical wind-shear exponent = 0.143
- Economic parameters: constant dollar COE in January 2002 dollars
- Fixed Charge Rate (constant dollar) = 11.85%
- Nominal (current dollar) discount rate = 9.25%
- Real (constant dollar) discount rate = 6.07%
- Turbine manufacturing volume: sufficient to produce 250 turbines per year, assuming prior production of 150 turbines
- Project Life = 30 years
- Plant size = 100 MW
- Capital Costs are in January 2002 dollars
- Plant start date = January 2003 (construction period is one year)
- Inflation = 3%
- Combined federal-state tax rate = 40%
- Land Lease Cost = \$0.00108/kWh in year 2002 dollars

Cost of Energy

The primary figure-of-merit is the levelized cost of energy, which is to be provided in constant, January 2002 dollars. COE is calculated for a 100 MW (rated) wind power plant, with an expected life of 30 years, using the following equation:

$$\text{COE} = \frac{(\text{FCR} \times \text{ICC}) + \text{AOE}}{\text{AEP}_{\text{net}}}$$

- where:
- COE ≡ Levelized Cost of Energy (\$/kWh) (constant dollar)
 - FCR ≡ Fixed Charge Rate (constant dollar) = (0.1185)
 - ICC ≡ Initial Capital Cost (\$)
 - AEP_{net} ≡ Net Annual Energy Production (kWh/yr)
 - AOE ≡ Annual Operating Expenses
≡ $\frac{\text{LLC} + (\text{O\&M} + \text{LRC})}{\text{AEP}_{\text{net}}}$
 - LLC ≡ Land Lease Cost
 - O&M ≡ Levelized O&M Cost
 - LRC ≡ Levelized Replacement/Overhaul Cost

Fixed Charge Rate

The Fixed Charge Rate is the annual amount per dollar of Initial Capital Cost needed to cover the capital cost, a return on debt and equity, and various other fixed charges. This rate is imputed from a hypothetical project, assuming GenCo balance sheet financing, modeled with NREL's FATE2-P pro forma cash flow spreadsheet model. Specifically, it includes construction financing, financing fees, return on debt and equity, depreciation, income tax, property tax and insurance. For the COE calculations, a constant dollar FCR = 0.1185 shall be used. The 10-year Section 45 Renewable Energy Production Tax Credit is not included in the Fixed Charge Rate and should not be included in the analysis.

Initial Capital Cost

The Initial Capital Cost is the sum of the Turbine System Cost and the Balance of Station Cost. Neither cost should include construction financing or financing fees, because these are calculated and added separately through the fixed charge rate. Neither cost should include a debt service reserve fund, which is assumed to be zero for balance sheet financing.

The Turbine System Cost shall be supported by a tabular listing of component costs and weights. Costs shall be based on a manufacturing volume of 250 turbines per year, assuming prior production of 150 turbines. In estimating the cost of components manufactured in-house, assembly labor and manufacturing overhead shall be included.

Thus, the stated cost should be the same as that developed in a "buy/make" analysis. The following breakdown of component costs shall be used.

- Rotor assembly
 - Blades
 - Aerodynamic control system
 - Rotor hub
 - Miscellaneous costs, including labor for factory assembly of rotor components
- Nacelle assembly
 - Low-speed shaft, bearings and couplings
 - Gearbox
 - Generator
 - Mechanical brake system
 - Mainframe (chassis)
 - Yaw system, including drives, dampers, brakes and bearings
 - Nacelle cover
 - Work platform
 - Miscellaneous costs, including labor for factory assembly of the nacelle
- Tower (less on-site assembly costs included in "installation" below)
- Control and electrical systems, including labor for factory assembly
- Shipping costs, including permits and insurance
- Warranty costs, including insurance
- Mark-up, including royalties, profit and overhead not included above

The Balance of Station Cost shall be supported by a tabular listing of the costs shown below.

- Wind resource assessment and feasibility studies
- Surveying
- Site preparation, including roads, grading and fences
- Electrical collection system infrastructure
- Substation
- Foundations for the wind turbines
- O&M facilities and equipment
- Receiving, installation, checkout and startup
- Wind power plant control and monitoring equipment
- Initial spare parts inventory
- Permits and licenses
- Legal counsel
- Project management and engineering
- Construction insurance
- Construction contingency

Annual Operating Expenses

Land Lease Cost

Annual Operating Expenses include Land Lease Cost, Levelized O&M Cost, and Levelized Replacement/Overhaul Cost, all expressed in units of \$/kWh. A levelized, constant-dollar land lease cost of \$0.00108/kWh in year 2002 dollars shall be used. (The levelized, current-dollar value is \$0.00146/kWh in year 2002 dollars.) This value was derived from a land lease term of 3% of revenues in the hypothetical GenCo case described. Because land lease payments are tax-deductible, the land lease cost specified above has already been multiplied by 60% (1 - 40%, where 40% is the combined tax rate).

Levelized O&M Cost

A component of AOE that is larger than the Land Lease Cost is O&M (Operations and Maintenance Cost). The O&M Cost shall include, and be supported by, a tabular listing of the following annual costs:

- Labor, parts and supplies for scheduled turbine maintenance
- Labor, parts and supplies for unscheduled turbine maintenance
- Parts and supplies for equipment and facilities maintenance
- Labor for administration and support

O&M should *not* include the land lease payment, which was included in the step above. O&M should *not* include property tax or insurance, as these are calculated separately and included with the Fixed Charge Rate. Because first-year O&M Cost is very close to the constant-dollar levelized expense, the first year value (in 2002 dollars) shall be used as a reasonable approximation of the levelized value. Because the first year of operation is 2003, if O&M cost is estimated in year 2003 dollars, it should be converted to 2002 dollars by dividing by 1.03 (1 + the rate of inflation). Because O&M is tax deductible, the final O&M value should be multiplied by 60% (1 - 40%, where 40% is the combined federal-state tax rate). Thus, the levelized O&M Cost calculation is:

$$\text{O\&M} = \frac{\text{First Year O\&M Cost (in 2002 dollars)} \times 0.60}{\text{AEP}_{\text{net}}}$$

Levelized Replacement/Overhaul Cost

Levelized Replacement/Overhaul Cost distributes the cost of major replacements and overhauls over the life of the wind turbine. This cost shall be supported by a tabular listing of:

- The year in which each replacement or overhaul is required relative to the year of installation, and
- Each replacement or overhaul cost including parts, supplies and labor, in current year dollars for the year of the replacement or overhaul

Downtime during replacements and overhauls shall be included in the determination of overall turbine availability. In the pro forma cash flow model, one “saves” for replacements and overhauls with deposits to a reserve fund in the years preceding the maintenance event. The repair is then depreciated using a straight-line convention. Consequently, both of these items – the major maintenance reserve fund and the repair depreciation – shall be incorporated into the calculation of Levelized Replacement/Overhaul Costs. To account for maintenance reserve fund payments, the following calculations shall be performed.

- (1) Use the following equation to determine the Present Value of each stream of reserve fund deposits incurred for each discrete replacement and overhaul event:

$$PV(n) \equiv PVF(n_{\text{midpoint}}) \times RC(2002) \times 1.03^n$$

where: $PV(n) \equiv$ Present Value of annual stream of reserve fund payments for event occurring in year (n)

$$PVF(n_{\text{midpoint}}) \equiv \text{Present Value Factor for mid-point year of reserve fund payment stream}$$

$$= (1 + i)^{-n_{\text{midpoint}}}$$

$i \equiv$ Nominal discount rate = (0.0925)

$RC(2002) \equiv$ Replacement/Overhaul Cost in year 2002
(in the formula above, 1.03^n is an inflation factor)

For example, if a replacement is made in year 10, the mid-point year (n_{midpoint}) is 5, because reserve fund payments are made from years 1 through 10. If second identical replacement follows in year 20, the mid-point year for that event is 15, because the reserve fund payments for that replacement were made from years 10 through 20. However, if replacement is made only in year 20, the mid-point year is 10.

- (2) Calculate the Levelized Replacement/Overhaul Cost (in constant dollars) by multiplying the sum of present values of the reserve fund payment streams by the Capital Recovery Factor.

$$LRC = CRF \times \sum PV(n)$$

where: $CRF \equiv$ Capital Recovery Factor
 $\equiv i_{\text{const}} / (1 - (1 + i_{\text{const}})^{-30})$
 $= (0.073)$

$i_{\text{const}} \equiv$ Constant dollar discount rate = (0.0607)

- (3) Multiply LRC by 0.80 to account for depreciation of each replacement (this factor was derived from the pro forma spreadsheet model described above)

Net Annual Energy Production

The Net Annual Energy Production shall be calculated for two Reference Sites, using wind-turbine performance specifications, estimated energy losses, and turbine availability. AEP calculations shall be supported by a tabular listing of the parameters shown below. Values in parentheses shall be used for the Reference Sites.

- Reference Site #1: annual average wind speed at a hub height of 10 m = (5.8 m/s)
- Reference Site #2: annual average wind speed at a hub height of 10 m = (6.7 m/s)
- Vertical wind-shear exponent = (0.143)
- Wind distribution table or specification = (Rayleigh)

Gross Annual Energy Production shall be calculated using the methodology described in the latest draft [1] of the International Electrotechnical Commission (IEC) Standard 1400-12. For calculations of COE, the wind speed range may be divided into 1.0 m/s bins rather than the IEC-specified 0.5 m/s bins. The following equations shall be used.

$$AEP_{\text{gross}} = N_h \sum_{i=1}^N [F(V_i) - F(V_{i+1})] [(P_i + P_{i+1}) / 2]$$

where:	AEP_{gross}	\equiv	Gross Annual Energy Production (kWh/yr/turbine)
	N_h	\equiv	Number of hours in one year
	= (8760)		
	N	\equiv	Number of wind speed bins
	V_i	\equiv	Wind speed in bin (i) (m/s)
	V_{i+1}	\equiv	Wind speed in bin (i+1) (m/s)
	P_i	\equiv	Power output in bin (i) (kW)
	P_{i+1}	\equiv	Power output in bin (i+1) (kW)
	$F(V)$	\equiv	Accumulated Rayleigh distribution
		$=$	$1 + \exp[-\pi/4 \times (V/V_{\text{hub, avg}})^2]$
	V	\equiv	Actual wind speed (m/s)
	$V_{\text{hub, avg}}$	\equiv	Annual average wind speed at hub height (m/s)
		$=$	$V_{10\text{m, avg}} \times (H_{\text{hub}} / 10)^\alpha$
	$V_{10\text{m, avg}}$	\equiv	Annual average wind speed at the Reference Site (m/s)
	H_{hub}	\equiv	Hub height (m)
	α	\equiv	Vertical wind shear exponent = (0.143)

Turbine Performance shall be tabulated as electrical power output at the bus bar versus wind speed at hub height. The table shall show power output for wind speeds from 0 to 25 m/s in 1.0 m/s increments starting with 0.5 m/s. If the table is based upon

measurements, normalizations and averaging using the IEC methodology, it shall identify which bins include "measured" data (based on three, 10-minute data sets) and which bins are extrapolations of measured data. If the table is based on projected performance, the rotor configuration and analysis method (e.g. PROP) shall be clearly stated.

Net Annual Energy Production shall account for energy losses and availability as follows.

$$AEP_{net} = AEP_{gross} \times (1 - EL) \times \text{Availability}$$

where: $EL \equiv$ Product of individual energy losses (% losses expressed as a decimal)
 $= 1 - (1 - L_{array}) \times (1 - L_{soiling}) \times (1 - L_{control}) \times (1 - L_{collect})$
 $L_{array} \equiv$ Array losses
 $L_{soiling} \equiv$ Blade soiling losses
 $L_{control} \equiv$ Controls and miscellaneous losses
 $L_{collect} \equiv$ Collection system losses from the turbines to the substation

Energy Losses and Availability shall be specified in a tabular listing. Availability is the ratio of the number of hours that the turbine was capable of operating during a certain period (excludes the number of hours that it could not operate because of maintenance or fault situations) to the total number of hours in the period.

Wind Resource Regimes

Using the methods described above, LWST cost-of-energy (COE) will be calculated at two wind regimes. The first is a Class 4 site, which has a Rayleigh distribution of wind speeds with a 5.8 m/s annual average at a height of 10 meters. The second is a Class 6 site, which has a Rayleigh distribution of wind speeds with a 6.7 m/s annual average at a height of 10 meters.

Wind Speed Bin Center (m/s)	Percent of Time At Wind Speed		
	Class 4 Site 5.8 m/s	Class 6 Site 6.7 m/s	Subcontractor-Selected Structural Design Site
0.5	2.31	1.73	—
1.5	6.61	5.02	—
2.5	10.04	7.81	—
3.5	12.22	9.85	—
4.5	13.04	11.01	—
5.5	12.63	11.30	—
6.5	11.30	10.84	—
7.5	9.41	9.79	—
8.5	7.35	8.40	—
9.5	5.41	6.86	—
10.5	3.75	5.35	—
11.5	2.46	3.99	—
12.5	1.53	2.85	—
13.5	0.90	1.96	—
14.5	0.51	1.29	—
15.5	0.27	0.82	—
16.5	0.14	0.50	—
17.5	0.07	0.29	—
18.5	0.03	0.16	—
19.5	0.01	0.09	—
20.5	0.01	0.05	—
21.5	0.00	0.02	—
22.5	0.00	0.01	—
23.5	0.00	0.01	—
24.5	0.00	0.00	—
V_{ave} @ 10 m	$V_{ave} = 5.8$ m/s @ 10 m	$V_{ave} = 6.7$ m/s @ 10 m	$V_{ave} =$ _____

The following equation shall be used to compute the wind speed as a function of height above the ground. For the COE Reference Sites, the wind shear exponent $\alpha = 0.143$. For the Design Site, the Subcontractor shall specify the wind shear exponent.

$$V(z) = V_{10m} (z/10m)^\alpha$$

Note that turbulence levels and extreme gust conditions used for design analyses are not described by the wind-speed probability distributions given above. These values shall be clearly defined by the Subcontractor and reported to NREL in appropriate deliverable reports.

References

1. *Wind Turbine Generator Systems - Part 12: Power Performance Measurement Techniques*. International Electrotechnical Commission (IEC), Technical Committee (TC) No. 88, Standard 1400-12, CDV Draft, February 8, 1994.

APPENDIX B

ATTU Subcontractor Data Input Worksheet

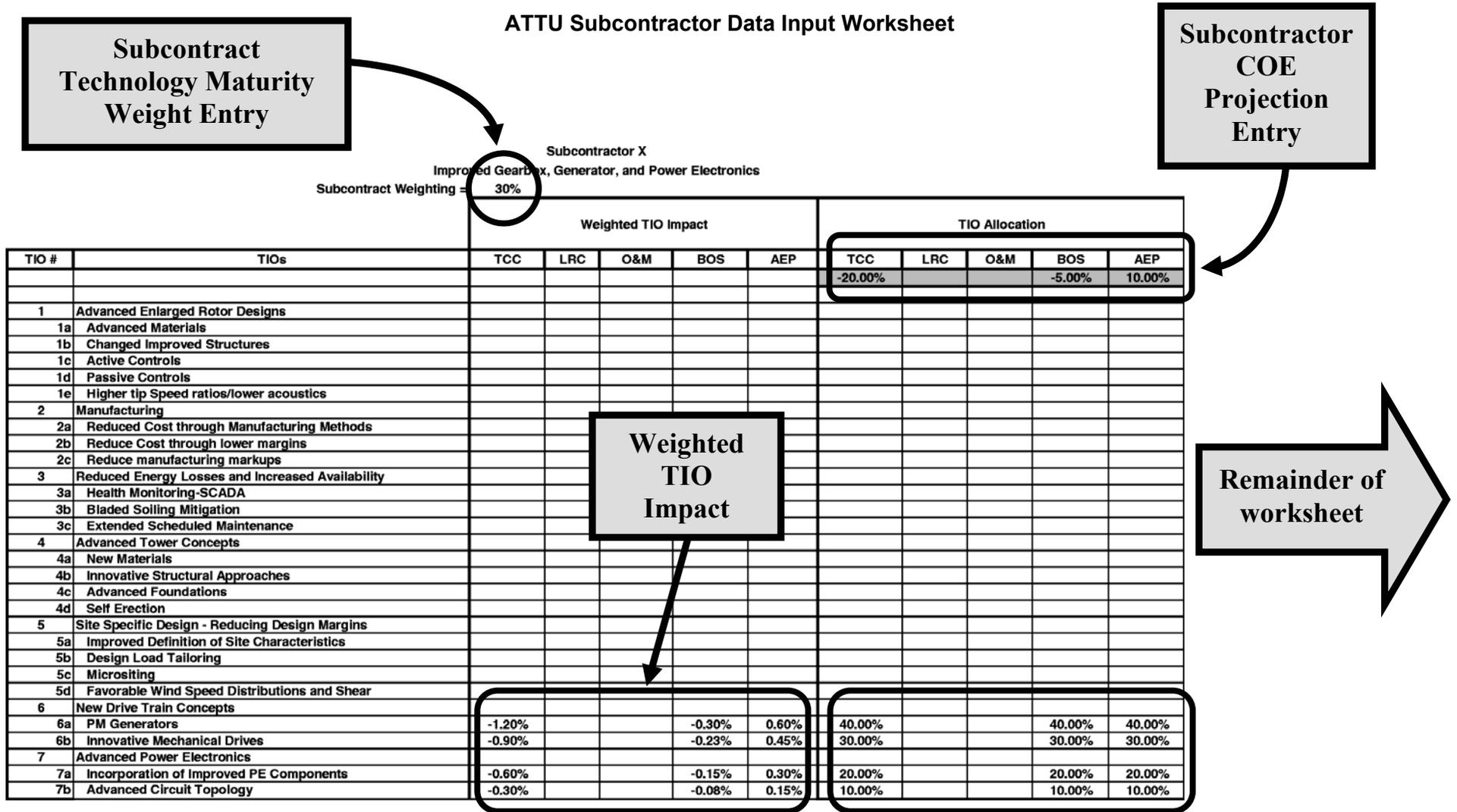


Figure B1a. ATTU subcontractor input worksheet (continued in Figure B1b).

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1. REPORT DATE (DD-MM-YYYY) June 2005		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE Low Wind Speed Technologies Annual Turbine Technology Update (ATTU) Process for Land-Based, Utility-Class Technologies				5a. CONTRACT NUMBER DE-AC36-99-GO10337		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) S. Schreck and A. Laxson				5d. PROJECT NUMBER NREL/TP-500-37505		
				5e. TASK NUMBER WER5.3200		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER NREL/TP-500-37505		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER		
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) The Low Wind Speed Technologies (LWST) Project comprises a diverse, balanced portfolio of industry-government partnerships structured to achieve ambitious cost of energy reductions. The LWST Project goal is: "By 2012, reduce the cost of energy (COE) for large wind systems in Class 4 winds (average wind speed of 5.8 m/s at 10 m height) to 3 cents/kWh (in levelized 2002 dollars) for onshore systems." The Annual Turbine Technology Update (ATTU) has been developed to quantify performance-based progress toward these goals, in response to OMB reporting requirements and to meet internal DOE program needs for advisory data.						
15. SUBJECT TERMS low wind speed technologies; wind energy; cost of energy						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18