NATIONAL ENERGY TECHNOLOGY LABORATORY

Existing Plants, Emissions and Capture – Setting Water-Energy R&D Program Goals

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Foreword

The original December 2006 report was updated in May 2008 to reflect Parson's May 2007 revision to the August 2005 report entitled "Power Plant Water Usage and Loss Study." The Parson's report was revised to correct an error in the calculation of the cooling water evaporation rate for a state-of-the-art wet recirculating cooling system. All values in this report impacted by the change in the cooling water evaporation rate were updated, including the values of levelized cost of freshwater conserved included in the recommended goal statement. No other changes were made to the report.

The original December 2006 report and May 2008 revision used water consumption (versus water withdrawal) of wet cooling technology to calculate the cost-effectiveness of dry cooling that was subsequently used to develop the cost targets. However, it was recognized that water withdrawal would be a better metric to develop the cost targets because all five of the DOE/NETL water-energy R&D technology categories result in reduction of freshwater withdrawal, whereas only four of the five categories result in reduction of freshwater consumption (Category B – increase cycles of concentration being the exception). Using water withdrawal to develop the cost targets will provide consistent and meaningful cost-effectiveness evaluations for all of the water-energy R&D technology projects being undertaken by DOE/NETL. Therefore, the November 2008 report changes the freshwater reduction metric from water consumption to water withdrawal. Also, the Appendix B cost comparison of wet and dry cooling water systems and corresponding levelized annual cost estimates were revised in the November 2008 report as follows: 1) costs escalated to 2008 dollars; 2) economic assumptions and resultant levelization factors updated; and 3) levelization method changed from constant dollar to current dollar basis. All values in this report impacted by these change were updated, including the values of levelized cost of freshwater conserved included in the recommended goal statement.

The May 2009 revision changes the recommended short- and long-term goal statements from alternative (1) to alternative (2) as shown on pages 5-6. Previous versions of the goal statements were based on alternative (1), in which the cost portion of the goal is stated as achieving a levelized cost in terms of dollars per thousand gallons of freshwater conserved. However, recent comments received from DOE/NETL management indicated that the alternative (1) cost goal was too absolute and did not adequately put the cost reduction in perspective. The alternative (2) cost goal is stated as achieving a levelized cost in terms of a percentage reduction compared to state-of-the-art dry cooling technology. Although removed from the goal statements, DOE/NETL will continue to use the levelized cost in terms of dollars per thousand gallons of freshwater conserved to measure the progress of its R&D projects. In addition, consistent with a recent change in program name, references to the Innovations for Existing Plants (IEP) R&D program in this report have been changed to the Existing Plants, Emissions and Capture (EPEC) R&D program.

Recommendation

It is recommended that the following goal statement be adopted for the water-energy R&D activity under the U.S. Department of Energy's National Energy Technology Laboratory (DOE/NETL) Existing Plants, Emissions and Capture (EPEC) R&D Program[1]:

> **"The short-term goal for the EPEC water-energy R&D activity is to have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology, while achieving a levelized cost savings of at least 25% compared to state-of-the-art dry cooling technology. The long-term goal is to have technologies ready for commercial demonstration by 2020 that, when used in combination, can reduce freshwater withdrawal and consumption by 70% or greater, while achieving a levelized cost savings of at least 50% compared to state-of-the-art dry cooling technology."**

Introduction

Since 2002, DOE/NETL has been conducting research to reduce the amount of freshwater needed by thermoelectric power plants and to minimize potential water quality impacts. The program sponsors research encompassing laboratory- and bench-scale activities through pilot-scale projects and is built upon partnership and collaboration with industry, academia, and other government and non-governmental organizations. The program is built around four specific areas of research:

- Non-Traditional Sources of Process and Cooling Water
- Innovative Water Reuse and Recovery
- Advanced Cooling Technology
- Advanced Water Treatment and Detection Technology

The original goal statement for the EPEC water-energy R&D activity was "to have technologies ready for deployment by 2015 that would lead to a 5-10% reduction in water withdrawal and consumption at thermoelectric power plants." However, DOE/NETL management had suggested the goal statement should be updated to reflect measurable cost and performance targets for the water-energy R&D activity. The purpose of this report is to recommend a new goal statement and provide appropriate documentation for the cost and performance measures.

Background

As mentioned above, the EPEC water-energy R&D activity is conducting research to reduce freshwater withdrawal and consumption at thermoelectric power plants. Withdrawal refers to the total quantity of water removed from a source while consumption refers to the portion of the withdrawn water that is not returned to the source (mostly being lost to evaporation). DOE/NETL estimates that U.S. thermoelectric power plants withdrew an average of 149 billion gallons per day (BGD) of freshwater in 2005, resulting in 6.2 BGD of freshwater consumption.[2]

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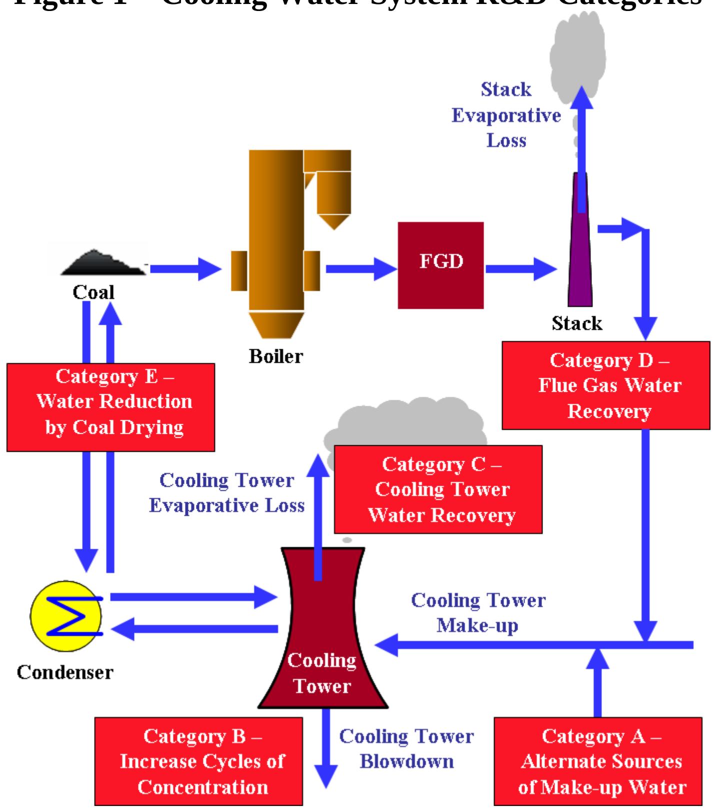
[1] Appendix C includes an abbreviated version of the goal statement for use in presentations.

[2] *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements*, Gary J. Stiegel, Jr., Andrea McNemar, Michael Nemeth, Brian Schimmoller, James Murphy, Lynn Manfredo, U.S. Department of Energy, National Energy Technology Laboratory, June 2006.

The majority of this freshwater use is required for the plant's cooling water system. As shown in Figure 1, DOE/NETL water-energy R&D is focused on five categories of technologies that can be applied to a wet recirculating cooling water system[3] to reduce freshwater withdrawal and/or consumption. The estimated percentage reduction in freshwater withdrawal and consumption for the five technology categories ranges from 5% to almost 30%. However, by combining technology categories, up to almost 60% reductions are possible for both withdrawal and consumption. Appendix A provides additional information on the water reduction capabilities of the five technology categories and a review of current water-energy R&D projects.

Figure 1 – Cooling Water System R&D Categories



Water-Energy R&D Goal Statement

A perceived shortcoming of the original water-energy R&D goal statement was its "outcome" based performance metric that would require a cumulative 5-10% reduction in water withdrawal and consumption at thermoelectric power plants by 2015. Such an "outcome" based metric becomes difficult to measure since the outcome is contingent on some unknown level of future technology implementation. Instead, the goal statement should be "output" based, which provides a means for direct and immediate measurement of technology development, not market penetration. The water-energy R&D goal statement should address both a short-term and long-term goal that includes measurable performance and cost components. The following goal

[3] The five technology categories are not considered for plants equipped with once-through cooling for two reasons: 1) categories B and C are only applicable to wet cooling towers; and 2) the potential water withdrawal savings associated with categories A, D, and E are negligible compared to the large volume of cooling water withdrawal necessary for once-through systems.

statements for the EPEC mercury control and advanced NOx control R&D activities can be used as a model:

Mercury Control – The near-term goal is to develop technologies that can achieve 50-70% mercury capture at costs 25-50% less than baseline estimates of $50,000-$70,000 per pound of mercury ($/lb Hg) removed. These technologies would be available for commercial demonstration by 2007 for all coal ranks. The longer-term goal is to develop advanced mercury control technologies that can achieve at least 90% capture and be available for commercial demonstration by 2010.

Advanced NOx Control - The short-term goal of the research is to develop advanced in-furnace technologies for coal-fired power plants capable of controlling NOx emissions to a level of 0.15 pounds per million Btu heat input (lb/MMBtu) by 2007 and 0.10 lb/MMBtu by 2010, while achieving a levelized cost savings of at least 25% compared to state-of-the-art selective catalytic reduction (SCR) control technology. The program's long-term goal is to further develop a combination of advanced in-furnace and SCR control technologies to achieve a NOx emission rate of 0.01 lb/MMBtu by 2020.

Both of these goal statements address short-term and long-term goals that include a performance and cost component. The performance components are similar – a percentage reduction in emission rate for mercury and a specific emission rate for NOx. However, the cost components are slightly different. The mercury cost component is based on a percentage cost reduction compared to previous baseline cost estimates for similar technology (activated carbon injection) expressed in dollars per pound of mercury reduction. The NOx cost component is based on a percentage cost reduction compared to the cost for an alternate technology (SCR) expressed in terms of levelized cost. Although the specific form or value of levelized cost is not defined in the goal statement, it can be presumed to be expressed in dollars per pound of NOx reduction.

A similar approach is recommended for the water-energy goal statement.

Target Dates

Without specific regulatory drivers, setting a year for technologies to be ready for commercial demonstration is somewhat arbitrary. However, it is recommended the short-term goal should be achieved by 2015 – the same year that is being targeted by current R&D activities. Setting the target date for the long-term goal at 2020 provides five additional years to enhance performance and reduce the cost of technologies developed to meet the short-term goal.

Performance Components

As discussed above, the EPEC water-energy R&D activities focus on five categories of technologies that can be applied to a wet recirculating cooling water system to reduce freshwater withdrawal and/or consumption. The five technology categories are not mutually exclusive, so that each of the technologies can be independently retrofit to an individual power plant. Rather than specify a performance goal for a specific technology, it is recommended that the goal be stated in terms of total reduction in water use achievable through the combined application of the five technology categories. This approach also enables new categories of technologies to be developed without requiring a change in the program goal.

Table 1 provides an estimate of potential freshwater reductions for 13 combinations of the five technology categories for a wet recirculating cooling water system on a coal-fired power plant based on an evaluation of on-going DOE/NETL water-energy R&D projects. Appendix A presents background information on the development of these freshwater reduction estimates for coal-fired plants and other types of thermoelectric generation. Based on this analysis, it is recommended that the short-term performance goal be stated as a 50% reduction in water withdrawal and consumption and the long-term goal a 70% reduction.

Table 1 – Potential Freshwater Reduction for a Wet Recirculating Cooling Water System at a Coal-Fired Power Plant

Technology Category Combination	Freshwater Withdrawal Reduction, %	Freshwater Consumption Reduction, %
A	27.0%	27.0%
B	11.1%	0.0%
C	20.0%	20.0%
D	3.8%	3.8%
E	5.6%	5.6%
AB	38.1%	30.4%
AC	47.0%	47.0%
BC	28.9%	20.0%
ABC	55.9%	50.4%
ABDE	46.9%	40.3%
ACDE	55.3%	55.3%
BCDE	36.7%	28.8%
ABCDE	63.7%	59.1%

Cost Components

Installation and operation of any of the five technology categories must be cost-effective. Since the performance goal of the water-energy R&D activity is focused on a reduction in freshwater use, the cost component should reflect a cost savings in terms of dollars per gallon of freshwater conserved. It is recommended that the cost difference between today's state-of-the-art wet recirculating cooling technology (using a steam condenser and wet cooling tower) and state-of-the-art dry cooling technology (direct dry cooling using an air cooled condenser) serve as the basis for determining the cost-effectiveness of the five technology categories.

Wet recirculating and dry cooling technology represent the two extremes for the purpose of the cost analysis. Current wet recirculating technology is a proven, cost-effective technology, but still requires significant quantities of freshwater to support power plant cooling. Wet recirculating cooling technology requires approximately 600 gallons per MWh of freshwater make-up.[4] Dry cooling completely eliminates water requirements to support power plant cooling, but is much more expensive than wet recirculating technology due to higher capital and operating costs, as well as an energy output penalty. The higher capital and operating costs result from the substantially more surface area and air flow that is required to accomplish an equal amount of heat transfer using air rather than water as a cooling medium. The energy

[4] "Power Plant Water Usage and Loss Study", May 2007, Parsons report for DOE/NETL. A subcritical pulverized coal (PC) plant requires 598 gal/MWh based on 149.5 gal/MWh of blowdown and 448.5 gal/MWh of evaporation. The blowdown rate assumes 4 cycles of concentration.

output penalty reflects the cost of capacity derates due to increased steam turbine backpressure during warm ambient temperature operation. In evaluating new technologies with respect to the proposed program goal, therefore, the cost per thousand gallons of freshwater conserved should be less than the incremental levelized cost of state-of-the-art dry cooling relative to current state-of-the-art wet cooling. Technologies that cannot achieve the performance goals at costs less than those for dry cooling should not be pursued.

Appendix B presents a cost comparison of wet versus dry cooling technology for a reference 500 MW coal-fired power plant based on 2008 dollars. The estimated current dollar levelized costs are 3.26 mills/kWh and 6.76 mills/kWh for wet and dry cooling, respectively.[5] As a result, the cost-effectiveness of dry cooling is estimated to be $5.86 per thousand gallons freshwater conserved (calculated by dividing the difference in the levelized cost between wet and dry cooling – 3.50 mills/kWh – by the wet cooling technology average water withdrawal rate – 598 gal/MWh). For the short-term water-energy goal, it is recommended that the cost-effectiveness of the R&D technologies be less than $4.40 per thousand gallons – equivalent to approximately 75% of dry cooling. For the long-term water-energy goal, it is recommended that the cost-effectiveness of the technologies be less than $2.90 per thousand gallons – equivalent to approximately 50% of dry cooling. Because the cost-effectiveness metric is measured in terms of cost per gallon of freshwater conserved, it can be used as a cost benchmark for individual technologies, as well as the five technology categories in combination.

Goal Statement Alternatives
Based on the above discussion, the following two alternative goal statements were considered for the EPEC water-energy R&D activity:

> (1) "The short-term goal for the EPEC water-energy R&D activity is to have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than $4.40 per thousand gallons freshwater conserved. The long-term goal is to have technologies ready for commercial demonstration by 2020 that, when used in combination, can reduce freshwater withdrawal and consumption by 70% or greater at a levelized cost of less than $2.90 per thousand gallons freshwater conserved."

> (2) "The short-term goal for the EPEC water-energy R&D activity is to have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology, while achieving a levelized cost savings of at least 25% compared to state-of-the-art dry cooling technology. The long-term goal is to have technologies ready for commercial demonstration by 2020 that, when used in combination, can reduce freshwater withdrawal and

[5] These are 20-year levelized costs calculated in current (i.e., real) dollars using 2008 as the base year.

> consumption by 70% or greater, while achieving a levelized cost savings of at least 50% compared to state-of-the-art dry cooling technology."

The alternative (1) goal statement, although stated in absolute cost terms, does not adequately put the cost reduction in perspective. The alternative (2) goal statement better puts the cost reduction in perspective since it is stated in terms of a percentage reduction compared to state-of-the-art dry cooling technology. Therefore, it is recommended the alternative (2) statement be selected as the EPEC water-energy goal. Although not included in the goal statement, DOE/NETL will continue to use the levelized cost in terms of dollars per thousand gallons of freshwater conserved to measure the progress of its R&D projects. Appendix C includes an abbreviated version of the goal statement for use in presentations.

Appendix A
Methodology to Develop Reduction in Water Withdrawal and Consumption

Reference: "Thermoelectric Freshwater Reductions Achievable With Advanced Water Technologies", July 2006 draft report prepared by RDS for DOE/NETL.

EPEC technology assessments

To evaluate the water impact of the EPEC technologies, assumptions had to be made regarding the amount of freshwater that each technology type would conserve in terms of reduced withdrawal and/or consumption. The discussion below details the assumptions and calculations used to arrive at percent water reduction estimates for each category. In cases where a project has not progressed to the point of presenting results, the analysis assumed that the outcomes projected by the technology developer would be achievable.

Table A-1 summarizes the percent reductions in water withdrawal and consumption for each of the 13 category calculations. In calculating the water savings for the primary and secondary categories, care must be taken to ensure the impacts are properly combined. In some cases, the impacts will be additive; in others, the impacts will have a more complicated relationship. The sections below describe the rationale for calculating the percentage reductions, first for the single technology categories and then for the technology combinations, using category AB as an example. The other primary and secondary combinations follow a similar analytic rationale.

Table A-1 – Water Withdrawal and Consumption Reductions by Technology Category

Scenario	Category Combination	Freshwater Withdrawal Reduction, %	Freshwater Consumption Reduction, %
1	A	27.0%	27.0%
2	B	11.1%	0.0%
3	C	20.0%	20.0%
4	D	Coal – 3.8% Fossil/Non-Coal – 5.9% Combined Cycle – 8.8% IGCC - 8.7%	Coal – 3.8% Fossil/Non-Coal – 5.9% Combined Cycle – 8.8% IGCC - 8.7%
5	E	5.6%	5.6%
6	AB	38.1%	30.4%
7	AC	47.0%	47.0%
8	BC	28.9%	20.0%
9	ABC	55.9%	50.4%
10	ABDE	Coal – 46.9% Fossil/Non-Coal – 48.9% Combined Cycle – 51.9% IGCC – 51.8%	Coal – 40.3% Fossil/Non-Coal – 42.6% Combined Cycle – 45.9% IGCC – 45.8%
11	ACDE	Coal – 55.3% Fossil/Non-Coal – 57.3% Combined Cycle – 60.3% IGCC – 60.2%	Coal – 55.3% Fossil/Non-Coal – 57.3% Combined Cycle – 60.3% IGCC – 60.2%
12	BCDE	Coal – 36.7% Fossil/Non-Coal – 38.7% Combined Cycle – 41.7% IGCC – 41.6%	Coal – 28.8% Fossil/Non-Coal – 31.1% Combined Cycle – 34.4% IGCC – 34.3%
13	ABCDE	Coal – 63.7% Fossil/Non-Coal – 65.7% Combined Cycle – 68.7% IGCC – 68.6%	Coal – 59.1% Fossil/Non-Coal – 61.4% Combined Cycle – 64.7% IGCC – 64.6%

Category A

Category A refers to projects in which an alternate water source is used to supplement or replace an existing freshwater source for cooling water makeup. Three EPEC projects fall under Category A:

- A1: *Use of Produced Water in Recirculated Cooling Systems at Power Generation Facilities & Development of an Impaired Water Cooling System* – EPRI
- A2: *Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Water for Thermoelectric Power Generation* – West Virginia University
- A3: *Reuse of Treated Internal or External Wastewaters in the Cooling Systems of Coal-Based Thermoelectric Power Plants* – University of Pittsburgh.

Projects in Category A are primarily applicable to thermoelectric plants equipped with recirculating cooling systems. The quantities of water available from these alternate sources would be too small to warrant recovery in plants equipped with once-through cooling systems.

Preliminary research results indicate that Projects A1, A2, and A3 would reduce freshwater withdrawal rates by 2 MGD, 3.6 MGD, and 4.0 MGD per recirculating plant location, respectively. The average reduction for the three projects, therefore, is 3.2 MGD per recirculating location.

To convert this quantity into a percent reduction for use in the analysis, it is necessary to determine the average total withdrawal rate per recirculating location. Because withdrawal rates differ by type of plant, the Platts *Power Plant Database* was used to determine the average withdrawal factor and total recirculating capacity for each fuel type. Those values (presented in Table A-2) were used to calculate a weighted average withdrawal factor, which is representative of all recirculating plants. The average recirculating plant capacity calculated from the database was found to be 781 MW. Average plant capacity is required because the alternate water source would likely be used across the plant's common cooling system, rather than per unit.

Table A-2 – Weighted Average Withdrawal Factor Calculation, Category A

	Average Plant Size (MW)	Total Recirculating Capacity (MW)	Withdrawal Factor (gal/h/kW)
Coal Subcritical	666	80,022	0.500
Coal Supercritical		65,528	0.642
Nuclear	1,487	42,445	1.101
Fossil Non-Coal	541	26,991	0.250
Combined Cycle	266	2,659	0.150
Weighted Average	**781**		**0.625**

The weighted average withdrawal factor and the average plant capacity were multiplied to obtain the average recirculating plant water use of 11.7 MGD. The percent withdrawal reduction was calculated by dividing the average water amount attributable to the alternate water source, 3.2 MGD, by the 11.7 MGD, resulting in 27%.

In terms of consumption, the alternate water source will be evenly split between the evaporative stream and the blowdown stream. Therefore, the percent consumption reduction is equal to the percent withdrawal reduction.

Category B

Category B refers to projects in which cooling water makeup requirements are reduced by increasing the cycles of concentration (COC) in a wet recirculating system. By increasing the cycles of concentration, blowdown is reduced, thereby reducing makeup requirements. Two NETL/EPEC projects fall under Category B:

- B1: *A Synergistic Combination of Advanced Separation and Chemical Scale Inhibitor Technologies for Efficient Use of Impaired Water in Coal-Based Power Plants* – Nalco Company
- B2: *Application of Pulsed Electrical Fields for Advanced Cooling in Coal-Fired Power Plants* – Drexel University.

Category B is exclusively applicable to plants equipped with recirculating cooling systems, but across all thermoelectric generation types.

Projects B1 and B2 both established goals for increasing the cycles of concentration: Project B1 from 2 to 10 and Project B2 from 3-4 to 8-10. A cursory analysis of the EIA-767 database, however, indicates that the average COC for thermoelectric power plants is closer to 5. For this analysis, therefore, it is assumed that Category B will result in an increase in COC from 5 to 10.

The following equations were used to evaluate the impact of COC on water withdrawal rates:

Make-Up = Evaporation + Blowdown + Drift
Blowdown = Evaporation/(COC – 1) – Drift
Make-up = Evaporation + Evaporation/(COC – 1)

Table A-3 summarizes the calculation of percentage reduction in cooling tower make-up water for varying levels of COC, assuming minimal drift and 100 nominal units of evaporation.

Table A-3 – Cycles of Concentration Calculations

Evaporation, units	Cycles	Blowdown, units	Blowdown % Reduction	Make-up, units	Make-up % Reduction
100	1	NA	NA	NA	NA
100	2	100.00	--	200	--
100	3	50.00	--	150	--
100	4	33.33	--	133	--
100	5	25.00	Base	125	Base
100	6	20.00	20.0%	120	4.00%
100	7	16.67	33.3%	117	6.67%
100	8	14.29	42.9%	114	8.57%
100	9	12.50	50.0%	113	10.00%
100	10	11.11	55.6%	111	11.11%

In shifting from COC=5 to COC=10, therefore, water withdrawal is reduced by 11.1%. There is no reduction in consumption; increasing the COC reduces blowdown requirements, but it does not have any impact on evaporation (consumption).

Category C

Category C refers to projects in which water is recovered from the evaporated water stream at thermoelectric power plants equipped with wet recirculating systems. One NETL/EPEC project falls in this category:

- C1: *Use of Air2Air™ Technology to Recover Fresh-Water from the Normal Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants* – SPX Cooling.

Category C applies to all thermoelectric plants equipped with wet recirculating systems.

Project C1 projected an average 20% water recovery rate from the evaporative water stream of a recirculating cooling water system. For negligible amounts of cooling tower drift, evaporation is related to blowdown by the following equation:

Blowdown = Evaporation/(COC – 1)

If the cycles of concentration are not changed, a 20% reduction in evaporation equates to a 20% reduction in blowdown. And since makeup (withdrawal) is the sum of blowdown and evaporation, the percentage reduction in makeup is the same as the percentage reduction in evaporation. Therefore, Category C results in withdrawal and consumption reductions of 20%.

Category D

Category D refers to power plants in which water is reclaimed from the combustion flue gas for use as cooling water makeup. Three NETL/EPEC projects fall in this category:

- D1: *Water Extraction from Coal-Fired Power Plant Flue Gas* – UNDEERC
- D2: *Recovery of Water from Boiler Flue Gas* – Lehigh University
- D3: *Reduction of Water Use in Wet FGD Systems* – URS Group, Inc.

Category D applies to all fossil steam thermoelectric power plants (coal and non-coal). The title of Project D3 indicates that this particular technology is exclusive to coal plants equipped with wet FGD systems, but Project D3 is actually just a narrowly defined application of Category D, so the calculations are the same as for Projects D1 and D2.

The projects in Category D discuss a projected 50% water recovery from the flue gas stream. It is assumed that this water is used to replace a portion of the cooling tower makeup, making it functionally equivalent to Category A. The percent withdrawal reduction, however, is heavily dependent on plant type; combined-cycle plants, for example, typically have more moisture in the flue gas than coal-fired plants. For coal plants, the percent withdrawal reduction is also dependent on coal type and type of FGD system. Lignite and sub-bituminous coals have more inherent moisture than bituminous coals, and plants with wet FGD systems have more flue gas moisture than plants with dry FGD systems. The percentage reduction in freshwater withdrawal and consumption used in the analysis ranges from 3.8% for coal-fired power plants to 8.8% for natural gas combined-cycle power plants.

To calculate the percentage reduction attributable to flue gas recovery for coal plants, data from the *Power Plant Water Usage and Loss Study*[11] provided flue gas moisture and cooling tower makeup quantities for a bituminous coal plant with no FGD. From this, a percentage withdrawal reduction was calculated. Data from the *Integrated Environmental Control Model*[12] was used to scale the percentage withdrawal reductions for all three coal types and all three FGD possibilities (no FGD, wet FGD and dry FGD). A weighted average for percentage withdrawal reduction was calculated based on the current U.S. distribution of coal plants by coal type and FGD type.

For natural gas combined-cycle and integrated gasification combined-cycle plants, data from the *Power Plant Water Usage and Loss Study* provided flue gas moisture and cooling tower makeup quantities from which percentage withdrawal reductions could be calculated. For non-coal fossil plants, the natural gas combined-cycle data was scaled up based on the relative difference in power between a combined-cycle unit and a non-coal fossil steam unit and the relative difference in plant efficiency.

<u>Category E</u>

Category E refers to projects in which evaporative losses are reduced by drying coal with energy derived from recirculating cooling water. One NETL/EPEC project falls in this category:

- E1: *Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants* – Lehigh University.

Category E applies only to coal plants, and more specifically, only to plants burning low-rank coals with high moisture contents.

The technology developed in Project E1 reduces evaporative losses from the cooling tower by recovering heat from the circulating water leaving the condenser and using that heat to dry coal. Since the temperature of the recirculating cooling water is reduced ahead of the cooling tower, evaporation losses are reduced as well. Results from Project E1 indicate a maximum evaporative loss reduction of 380 gpm for a 550 MW power plant when recovering heat solely from the recirculating cooling water.

Project E1 did not provide cooling water flow data from which to calculate the water savings as a function of withdrawal and consumption. Therefore, data from the *Power Plant Water Usage and Loss Study* was scaled to estimate the resulting water savings. The subcritical coal-fired power plant in the *Power Plant Water Usage and Loss Study* had a net capacity of 521 MW and a cooling tower evaporation rate of 6,415 gpm. Scaling this evaporative load to the 550 MW plant evaluated for Project E1 results in a value of 6,772 gpm. Reducing the evaporative, or consumption, losses by 380 gpm is equivalent to a 5.6% reduction.

For negligible amounts of cooling tower drift, evaporation is related to blowdown by the following equation:

Blowdown = Evaporation/(Cycles of Concentration – 1)

If the cycles of concentration are not changed, the percentage reduction in evaporation is the same as the percentage reduction in blowdown. And since makeup (withdrawal) is the sum of blowdown and evaporation, the percentage reduction in makeup is the same as the percentage reduction in evaporation. Therefore, Category E results in withdrawal and consumption reductions of 5.6%.

Primary and Secondary Combinations

The primary and secondary technology combinations demand careful evaluation to accurately combine the separate impacts on water withdrawal and consumption. The calculation of percentage reduction in freshwater withdrawal and consumption for each primary and secondary combination is contained in the Excel spreadsheet model that accompanies this report. Primary combination AB is examined below to illustrate the analytic approach.

To understand the water reductions attributable to Category AB, it's best to consider the cooling system of a hypothetical plant and use the following equations:

Make-Up = Evaporation + Blowdown + Drift
Blowdown = Evaporation/(COC – 1) – Drift

For a cooling system with cycles of concentration equal to 5 and an evaporative load of 100 gpm, the corresponding blowdown is 25 gpm and the makeup rate is 125 gpm. Applying Category B, if the cycles of concentration is raised from 5 to 10, the evaporative load stays at 100 gpm, but the blowdown falls to 11.1 gpm and the makeup rate falls to 111.1 gpm. Next, in applying Category A, 27% of the initial freshwater makeup, 33.8 gpm, is replaced with an alternate water source. The freshwater makeup, therefore, has gone from 125 gpm to 77.4 gpm, equivalent to a 38.1% reduction as reported in Table A-1.

To calculate the consumption reduction, it is necessary to adjust the evaporative load by the amount of freshwater reduced as a result of incorporating the alternate water source. Dividing the freshwater makeup remaining *after* applying Category A by the freshwater makeup *before* applying Category A, one can determine how the fresh water and alternate water are distributed in the evaporative and blowdown streams. This results in a 69.6% /30.4% split between freshwater and alternate water. The evaporative stream, therefore, goes from 100 gpm to 69.6 gpm, equivalent to a 30.4% consumption reduction.

Appendix B
Cost Comparison of Wet and Dry Cooling Water Systems
for a Reference 500 MW Coal-Fired Power Plant

Cost Component	Wet Cooling (2008$)	Direct Dry Cooling (2008$)	Delta
Equipment Capital Cost			
Capital cost, $/kW	104	228	124
Total capital requirement, Million $	52.1	114.0	62
First year carrying charge, (1,000 $/yr)	10,935	23,944	13,009
Annual Operation & Maintenance Cost (x1,000)			
Maintenance	521	1,140	619
Water treatment	896	0	-896
Auxiliary power	1,051	2,102	1,051
Lost capacity penalty	0	1,051	1,051
Total annual O&M	2,467	4,294	1,826
Total First Year Costs			
$/yr (x1,000)	13,403	28,238	14,835
COE, mills/kWh	3.82	8.06	4.23
$/1000 gallon water conserved	NA	NA	7.08
Levelized Annual Cost (Current $)			
$/yr (x1000)	11,407	23,688	12,281
COE, mills/kWh	3.26	6.76	3.50
$/1000 gal water conserved	NA	NA	5.86

Appendix B
Cost Comparison of Wet and Dry Cooling Water Systems for a Reference 500 MW Coal-Fired Power Plant

Cost & Performance Assumptions:	Value	Reference
Annual inflation rate, %	3.0%	
Plant capacity, MW	500	
Capacity factor, %	80%	
Wet tower capital cost, $/kW (2008$)	104	(1) & (5)
Capital cost adder for dry tower (2008$)	124	(3) & (5)
Fixed maintenance as % capital cost, %	1.0%	(1)
Water treatment, $/kW-yr (2002$)	1.5	(1)
Aux. power as % plant capacity (Wet)	1.0%	(2)
Aux. power as % plant capacity (Dry)	2.0%	(2)
Lost capacity penalty, % (Dry)	1.0%	(2)
Energy cost, $/kWh	0.030	(1)
Water make-up @ full load, gal/MWh	598	(4)

Levelization Factors:	Current $	Reference
Levelization factor for O&M	1.162	(6)
1st year capital charge factor	21.0%	(7)
Levelized capital charge factor	16.4%	(6)

References:

(1) "An Investigation of Site-Specific Considerations for Retrofitting Recirculating Cooling Towers at
Existing Power Plants - A Four-Site Case Study", May 2002, Parsons report for DOE/NETL

(2) EPRI August 2004 report #1005358 titled "Comparison of Alternate Cooling Technologies for U.S. Power Plants:
Economic, Environmental, and Other Tradeoffs"

(3) Capital cost adder for dry cooling system based on average dry vs. wet delta capital cost from two references:
Burns & McDonnell evaluation for Sempra Energy, November 2002 - 76 $/kW adder (dry @ 172 $/kW vs. wet @ 96 $/kW)
EPRI August 2004 (see reference 2) - 99 $/kW adder (dry @ 135 $/kW vs. wet @ 36 $/kW)

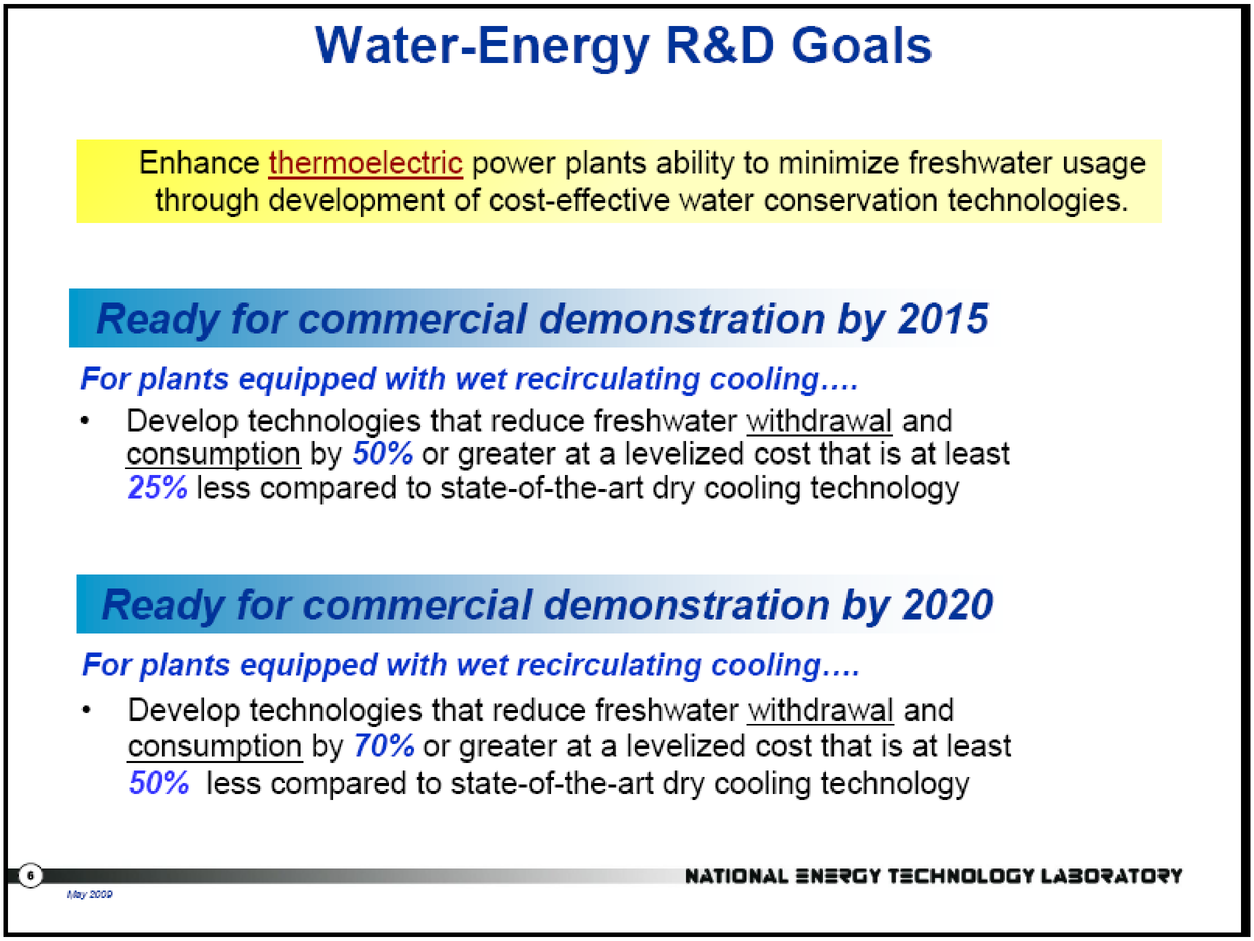
(4) "Power Plant Water Usage and Loss Study" , May 2007 Update to August 2005 Parsons report for DOE/NETL.
Subcritical power plant cooling system make-up per Table 7-6.

(5) Capital costs escalated to 2008$ using Chemical Engineering Plant Cost Indices
2002 @ 395.6; 2004 @ 444.2; and 2008 @ 597.1
2008 cost index per June 2008 data

(6) Parsons Corporation study for DOE/NETL "Cost and Performance Baseline for Fossil Energy Plants -
Volume 1: Bituminous Coal and Natural Gas to Electricity", Revision 1, August 2007.

(7) NETL internal calculation based on EPRI's Technical Assessment Guide (TAG) methodology.

Appendix C
EPEC Water-Energy Goal Statement –
Abbreviated Version for Presentations



Slide Notes Section:

Dry cooling can reduce freshwater usage by 100%, but at a high cost due to greater capital cost and energy efficiency penalties.
NETL estimated cost of water conservation using dry cooling is $5.86 per thousand gallons as compared to wet recirculating cooling.
Therefore, water-energy R&D project technologies required to achieve freshwater reductions at a cost of less than $4.40 per 1,000 gallons (25% less than dry cooling) for the 2015 goal and by less than $2.90 per 1,000 gallons (50% less than dry cooling) for the 2020 goal.