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U.S. DEPARTMENT OF ENERGY

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Crosscutting Technologies in Carbon Dioxide Capture and Storage

Chapter 4: Technology Assessments

Overview of Crosscutting Technologies in Carbon Dioxide Capture and Storage

Investments in innovative technologies that support multiple aspects of fossil fuel utilization are pushing the forefront of carbon capture and storage technologies and clean fossil power production. Improved performance of fossil-based power-generation systems results in significant reductions in CO_2 emissions, thereby decreasing the associated requirements for carbon capture and storage. Targeted advancements in high-performance materials, sensors and control technology, and application-focused modeling and simulation tools serve as a bridge between basic and applied research as well as open opportunities by providing tools to enhance the availability and efficiency of advanced power systems. Special attention to water management is an area of rising importance which impacts efficiencies and carbon footprints.

The integrated nature of future advanced fossil fueled plants requires a multidisciplinary research and development approach to advanced enabling technologies and tools which benefit both existing and new advanced energy systems. Crosscutting technology research serves to incubate and foster the growth of novel concepts that hold the potential to advance coal-fueled power systems and Carbon Capture and Storage (CCS) technologies. CCS also includes CO_2 utilization where appropriate. Quick assimilation of successful innovative technology developments is possible in the crosscutting technologies due to their multidisciplinary nature, which is frequently enhanced by direct participation from industry (both customers and suppliers). These efforts help to develop the technology solutions that will be used by the power generation sector (from small municipal to larger utilities) in order to meet future environmental needs. Key crosscutting technologies examined here include the following:

- **Sensors and Controls** – advanced sensors, measurement tools, and controls which manage complexity, lower costs and enable robust monitoring and real-time optimization of fully integrated, highly efficient power-generation systems.
- **Structural and Functional High Performance Materials** – to lower the cost and improve the performance of fossil-based power-generation systems.
- **Simulation-Based Engineering** – to achieve a computational representation of the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant.
- **Water Management** – to remove barriers to sustainable, efficient water and energy use, developing technology solutions, and enhancing understanding of the intimate relationship between energy and water resources.

As a collection of advanced capabilities, each technology area has distinct R&D challenges. This technology assessment includes a discussion of each technology area. For each technology area a chart highlights key targeted needs, current research thrusts, and pathways to address the challenges and achieve the targeted outcome. Links and references are included for further in-depth information.

Sensors and Controls

Current research is underway to develop sensors and measurement tools that manage complexity, lower costs and enable robust monitoring and real-time optimization of fully integrated, highly efficient power-generation systems. Sensors often operate in harsh conditions. Harsh conditions vary throughout a power plant on a component-by-component basis. Examples include gas turbines (combustion temperatures in excess of 1500°C), boilers (760°C and 34MPa steam conditions), gasifiers (1300–1800°C), etc. There are a host of other considerations including vibrations, reducing/oxidizing environments, shock, and corrosion that a deployed sensor must also be able to withstand. Survivability, durability, and robustness are key issues for sensors under these harsh environment conditions. A critical challenge is to make sensors that are reliable and maintenance-free to ensure adoption by power plant operators. Controls research centers around self-organizing information networks and distributed intelligence for process control. The reliability of these systems is promoted by the networking of sensors and the use of improved decision-making capabilities. These issues are detailed in Tables 4.G.1 and 4.G.2.

Table 4.G.1 Challenges and Desired Outcomes for Sensors and Controls

Sensors and Controls - develop advanced sensors, measurement tools, and controls which manage complexity, lower costs, and enable robust monitoring and real-time optimization of fully integrated, highly efficient power-generation systems.

Major R&D Challenges

- withstanding harsh thermal, mechanical, and chemical conditions to ensure suitable operational life and reliability[1,2]
- developing novel materials, designs, and packaging concepts to support resistance to harsh environments
- developing control schemes for condition assessment, monitoring, and optimization across multiple components
- advancing information-intensive sensor systems to expand operational capabilities
- assuring reliable and maintenance-free operation to enable adoption by power plant operators

Desired Outcomes

- enabling 2nd generation CCS technology goals through deployment of advanced sensing
- demonstrating advanced in-process monitoring and control
- establishing a clear pathway to an effective broad implementation of the next-generation sensor technology

Table 4.G.2 Technical Assessment and Opportunities for Sensors and Controls

Sensors and Controls - develop advanced sensors, measurement tools, and controls which manage complexity, lower costs and enable robust monitoring and real-time optimization of fully integrated, highly efficient power-generation systems.		
State of the Art[3]	Current R&D	Opportunities and Future Pathways
■ The use of advanced sensors and controls lead to increases in efficiency and plant reliability/availability.[4] The average annual plant revenue loss from 2007 to 2011 due to forced outages and de-rates for boilers in 600-799 MW plants was ~$10 million dollars.[5] ■ Real-time integration and coordination of power generation technologies has improved overall system performance and reliability assessment.[6] ■ Sensors and Controls can facilitate increases in heat rate and availability for the existing coal-fired power plant fleet. ■ An increase in availability by 1% via sensor measurements that successfully minimize unplanned outages and lower plant downtime due to maintenance would yield 15 million MWh/year of additional generation (equivalent to 2.1 GW of additional capacity) from the existing fleet.[7]	■ Sensor capabilities (including temperature, pressure, and gas composition) for high temperature, high pressure, and/or corrosive environments of a power system or underground injection system.[8,9] ■ Optical sensors, microsensors, embedded sensors, imaging, and enabling technologies such as wireless energy harvesting and advanced manufacturing.[10] ■ Single point, distributed, and multiplexed sensors. ■ Materials for active sensing layers and protective coatings should incorporate the effects of temperature gradients during temperature cycling.[11,12,13] ■ Algorithms for image reconstruction ■ Microfabrication techniques such as direct write and thermocompression bonding. ■ Active wireless communication and interrogation techniques.[14] ■ New control architecture approaches that mimic biological systems, utilize distributed intelligence, and are designed to handle complexity that is inherent to advanced energy systems, including integrated sensor networking and placement.[15] ■ Computational models and experimentation to determine the optimal number of sensors, sensor placement, schemes to address large temporal and spatial variations, and adaptive architectures.	■ A higher level of design and system integration for embedded sensors will require the use of high-temperature conductive ceramics, piezoelectric ceramics, elevated temperature electronics, wireless data transfer, and self-powering capability. ■ Novel sensor packaging methods should include computational efforts to predict with acceptable uncertainty the life of a given sensor within relevant harsh environments, including novel packaging geometries, base materials and coatings. ■ New facilities for sensor testing to assure reliable and maintenance-free operation would aid in proving survivability while maintaining optimal performance and evaluating portability, connectivity, and in-service deployment. ■ Simulation environments that emulate advanced energy systems with complex, non-linear component interactions could be used as a platform to test and verify performance with novel control methods using real time and novel control methods. ■ Control strategies that are verified via simulation environment could then be deployed in a pilot-scale test facility that features hardware-in-the-loop (hybrid hardware/software configuration) capability.

Advanced Materials

Advanced structural and functional materials have potential to lower the cost and improve the performance of fossil-based power-generation systems. Computational tools can support predictive performance with acceptable levels of uncertainty, improve understanding of failure mechanisms, and guide the design of new materials capable of operation under extreme temperature, pressure, and corrosive conditions in future coal-fueled power plants. These tools would assist in decreasing the time and cost required to develop new materials compared to traditional trial-based methodologies. Advanced manufacturing technologies are being developed to economically fabricate components that cannot be made using conventional techniques. These issues are detailed in Tables 4.G.3 and 4.G.4.

Table 4.G.3 Challenges and Desired Outcomes for Structural and Functional High Performance Materials

Structural and Functional High Performance Materials
Goal: Lower the cost and improve the performance of fossil-based power-generation systems using improved materials.

Major R&D Challenges

- reducing time and cost to develop and qualify new materials for advanced fossil applications
- reducing costs of components from complex high performance materials for advanced power generation technologies
- predicting long term (up to 300,000 hours) mechanical and corrosion behavior of advanced materials with computational models validated by targeted testing
- reducing costs of high performance structural and functional materials through substitution of less costly materials
- effective joining of high performance materials
- successfully modeling advanced fabrication methods and predicting the performance of production for large complex structural components in order to reduce production time and ensure material integrity

Desired Outcomes

- developing advanced materials for extreme environments
- decreasing by a factor of 2 the time and cost of developing, validating, and qualifying new alloys
- demonstrating advanced manufacturing techniques for key components made from high performance materials
- reducing component fabrication cost and total life cycle cost
- demonstrating nickel super alloy components in an operational environment for advanced ultra-supercritical coal fired boiler[16]
- developing supply chains for extreme environment materials

Table 4.G.4 Technical Assessment and Opportunities for Structural and Functional High Performance Materials

<table>
<tr><th colspan="3">Structural and Functional High Performance Materials
Goal: Lower the cost and improve the performance of fossil-based power-generation systems.</th></tr>
<tr><th>State of the Art[17,18,19,20]</th><th>Current R&D</th><th>Opportunities and Future Pathways</th></tr>
<tr>
<td>■ Polycrystalline precipitation strengthened nickel superalloys test data shows minimum life of 100,000 hours in steam and coal combustion atmospheres at temperatures and steam pressures up to 760°C and 5000 psi. Ability to fabricate and weld nickel alloys has been demonstrated.
■ Computational materials design tools used to improve alloys (9Cr rotor steel) at reduced time and cost (large casting homogenization design).
■ Advanced joining method “friction stir welding” has shown improved mechanical properties of joints in the laboratory.
■ Effects of oxy-combustion firing conditions on the corrosion of metal alloys measured in simulated coal combustion environments.
■ Creep of high performance materials was successfully described using statistically valid physics-based models to show behavior over a wide range of temperatures and applied stresses.</td>
<td>■ Supporting R&D to help enable supply chain development for nickel superalloy components in advanced fossil power generation systems.[21]
■ New and lower cost structural and functional materials for advanced fossil power generation systems.
■ Advanced manufacturing methods (including Additive Manufacturing and Hot Isostatic Pressure of Powdered Metal (HIP/PM) for high nickel components.
■ Additive manufacturing innovation and infrastructure and advanced joining methods from other industries to accelerate application.
■ Advanced[22] computational design and predictive modeling tools and methods to address:
- high cost of advanced materials, components and assemblies;
- durability of materials under extreme conditions (temperature, pressure, corrosive environment of advanced fossil-fueled processes and existing fossil-based power generation fleet);
- New structural materials requirements for advanced power systems.</td>
<td>■ Develop the capability to pour high Ni alloys at additional domestic foundries with high melt capacity.
■ Design, build, and test AUSC high performance materials components and validate through demonstration in an operational environment.
■ Increase high temperature properties in powdered metal super alloy components by varying temperature cycles in Hot Isostatic Pressure of Powdered Metal and new high temperature protocols designed specifically for powdered metal components.
■ Identify and test lower cost high performance materials for advanced fossil power applications, such as diffusion bonding of super alloy powdered metal.
■ Identify and test improved and lower cost oxygen carriers for chemical looping combustion (CLC) and post combustion CO2 sorbents.
■ Identify and test advanced manufacturing and joining methods for specific high performance materials and components, where current fabrication methods are either very expensive or cannot technically be used.
■ Develop integrated suites of computational materials design and long term performance modeling tools that are specifically designed to address the unique issues and requirements of advanced fossil power technologies. These specific unique issues include long term corrosion/oxidation, creep, creep-fatigue and cyclic thermomechanical fatigue degradation of structural materials operating at elevated temperatures and pressures.
■ Develop crosscutting applications with other high temperature systems, such as nuclear, for the purpose of expanding marketability and reducing manufacturing costs
■ Develop materials to handle the corrosive gases and particle number concentration challenge at elevated pressures</td>
</tr>
</table>

Simulation-Based Engineering

Simulation-based engineering builds upon a vast amount of expertise and capability to computationally simulate the full range of energy science from ab initio calculations at the molecular level and molecular dynamic simulations, through reactive and multiphase flows, up to a full-scale virtual and interactive power plant. Science-based models of the physical phenomenon occurring in fossil fuel conversion processes and development of multi-scale, multi-physics simulation capabilities are just some of the tools and capabilities needing further development in order to help improve these systems. Research and development activities that are needed include developing a framework to quantify uncertainties and assess the impact of their propagation in the models, providing quantitative uncertainty ranges on simulation data, creating simplified models to balance the needs of accuracy and time-to-solution, and model validation. These issues are detailed in Tables 4.G.5 and 4.G.6.

Table 4.G.5 Challenges and Desired Outcomes for Simulation-Based Engineering

Simulation-Based Engineering - computationally represent the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant.

Major R&D Challenges

- reducing the time to solution while maintaining or increasing model fidelity for increased confidence in tools
- integrating models across scales as well as across toolkits to utilize information generated through previous studies
- quantifying and reducing the uncertainty associated with computational tools

Desired Outcomes

- expansion of applications and commercial deployment of toolsets, as well as expansion of open source software capabilities to provide industry with robust software packages to accelerate deployment of next generation and transformational advanced energy system technologies.
- deployment of toolsets to fully demonstrate the capability to accelerate novel carbon capture technologies and to help meet the integrated 2nd generation target of $40/tonne CO_2 capture cost.

Table 4.G.6 Technical Assessment and Opportunities for Simulation-Based Engineering

Simulation-Based Engineering[23] - computationally represent the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant.

State of the Art	Current R&D	Opportunities and Future Pathways
■ Computational information across scales and related information is successfully being linked with uncertainty quantification. ■ Advanced integration tools are expected to reduce technology development time and cost.[24] ■ Studies using open source software have demonstrated the ability to save on design and construction costs by modifying system designs (e.g., modifying design from double wall to a single wall vessel)[25] ■ Time to solution over conventional kinetic and chemistry models have been improved by 100x+ in open source software and kinetics reduced order models (ROMs).	■ Uncertainty quantification and code improvements[26] are striving to achieve a 20% increase in the fidelity of multiphase models and 50% decreased time-to-solution while addressing multi-scale, multi-physics simulation capabilities to couple fluid flow, heat- and mass-transfer, and complex chemical reactions for optimizing the design and operation of unit processes in advanced power generation systems. ■ Computational formats for domain specific solution sets (e.g., materials design,[27] chemical looping, dynamic design and optimization of integrated power systems), and tools to optimize data handling and to exploit information technology in the design of advanced energy systems are under development. ■ A comprehensive integrated suite of tools is used to predict the performance of ADA's pilot-scale 1 MW solid sorbent capture process system and assess various heat integration concepts. This in turn is enabling the hierarchical validation of solid sorbent reactor models.[28] ■ Models for prediction of pulverizer performance in oxy-combustion boilers are being validated with data from manufacturers. ■ Pilot-scale data from the National Carbon Capture Center is providing a comprehensive validation of a solvent-based carbon capture system mode ■ Initial studies have shown that heat rate can be improved by 200-400 Btu/kWh by optimizing combustion in the boiler.	■ Expansion of applications and commercial deployment of advance modeling tools. ■ Expansion of open source software capabilities. ■ Large scale validation and verification to provide industry with robust software packages to accelerate deployment of next generation advanced energy system technologies. ■ Further reduction in time to solution and uncertainty through continued development of application-specific modeling tools optimized for each application and through strategic experimental validation. ■ Collaborative engagement with industry, both customers and suppliers, can address technology transfer challenges to advance from labs into production and usage. ■ Model development and validation under extreme combustion conditions, e.g. high temperature and/or pressurized oxy-combustion. ■ Integration of complex unit models, e.g. combustion model of a boiler, with dynamic system (plant) model.

Water Management

Current average water usage for US thermoelectric power generation is 19 gallons of water per kilowatt hour (kWh) electricity generated.[29] This includes water withdrawals for both once-through and closed-loop systems. Consumption of water (due to evaporation from the cooling system and other purposes) is roughly 0.5 to 1.0 gallons of water per kWh for a typical coal-fired steam plant.[30] Upgrading the efficiency of power generation would significantly reduce this water usage. Among existing U.S. coal fired power plants, the most efficient U.S. coal-fired plant is the John W. Turk ultra-supercritical plant with a heat rate of 8,858 Btu/kWh. This heat rate is 16% lower than the US coal fleet average, resulting in lower water usage as less waste heat must be removed from the power plant. More-efficient thermoelectric generation reduces the amount of cooling (and therefore water) required. More broadly, the cooling system deployed impacts the water consumption and withdrawal more significantly than power generation technology.[31] With all other factors being equal, the transition from once-through cooling to recirculating cooling that has been underway for several decades has and will continue to reduce withdrawals, which are in the range of roughly 10,000 to 40,000 gallons per MWh, but increases consumption, which is in the range of roughly 100 to 400 gallons/MWh for a once-through plant to roughly 500 to 1000 gallons/MWh for a closed-loop plant.[31,32]

Research addresses the need to reduce the amount of freshwater used by power plants and to minimize any potential impacts of plant operations on water quality. This can be accomplished through a variety of means (e.g. efficiency gains, improvements in water recovery and reuse, advanced (low-water) cooling systems, or through the use of alternative sources of water). This is especially important with the increasing prevalence of drought in the United States, particularly in the South and Western U.S. A national effort directed at ensuring sustainable, efficient water and energy use, developing technology solutions, and enhancing understanding of the intimate relationship between energy and water resources to lower water usage per megawatt of electricity generated would need crosscutting research. These issues are detailed in Tables 4.G.7 and 4.G.8.

Table 4.G.7 Challenges and Desired Outcomes for Water Management

Water Management - removing barriers to sustainable, efficient water and energy use, developing technology solutions, and enhancing understanding of the intimate relationship between energy and water resources.[33]

Major R&D Challenges

- reducing water usage and impact on water quality of fossil energy production and utilization
- decreasing waste heat output and water usage of electricity generation
- lessening impacts of water on fossil fuel extraction and carbon storage

Desired Outcomes

- increase the efficiency of water usage within power systems significantly

Table 4.G.8 Technical Assessment and Opportunities for Water Management

Water Management - removing barriers to sustainable, efficient water and energy use, developing technology solutions, and enhancing understanding of the intimate relationship between energy and water resources.

State of the Art	Current Research	Opportunities and Future Pathways
■ Hybrid cooling, advanced dry cooling with desiccant, water recovery from flue gas and cooling tower. ■ SPX ClearSky Plume Abatement Cooling Tower[34] and DryFining™, the commercial name of the drying process using waste heat[35] (Power Engineering magazine's 2010 "Best Coal-Fired Project") ■ Significant advanced cooling options to increase plant efficiencies have been identified.	Power plant waste heat use projects: ■ recovering heat and water from flue gas, ■ developing a field demonstration of existing heat and water recovery techniques at coal-fired power plants, ■ using forward osmosis and waste heat to remove CO_2 from flue gas and treat degraded water.[36] Cost effective treatment of produced brine (also applicable to many oil and gas produced waters): ■ advanced water treatment membranes (examples are: forward osmosis membranes with waste heat, nanoporous ceramic membrane), turbo-expander for brine freeze desalination, and others.[37] Brine freeze analysis of droplets is defining minimum freeze conditions for drop size and injection energy.[38]	■ Minimize the impact of electricity generation on water availability and quality. ■ Support enhanced efficiency of existing pulverized coal plants and advanced energy systems with higher efficiency and therefore lower water usage. ■ Integrate CCS with water conservation methods.[39] ■ Identify opportunities to couple cooling with non-traditional power generation cycles. ■ Evaluate state-of-the-art technology for cleaning produced water. ■ Produce a 'Best Practices Manual' for water management in CCS systems. ■ Build data and develop models to better understand the linkage between thermoelectric power generation and water (surface water, groundwater, municipal wastewater, and shallow brackish groundwater).

Endnotes

1 EPRI, 2006, TR-1010462, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001010462

2 EPRI, Dec 2003, TR-1003732, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001003732

3 IEA, June 2015, Clean Coal Centre Profile No 21, ,http://www.iea-coal.org.uk/documents/83703/9401/Advanced-sensors-and-smart-controls-for-coal-fired-power-plant,-CCC/251

4 Nalbanian, 2005, IEA, Clean Coal Centre report, ISBN:92-9029-416-7 http://www.iea-coal.org.uk/reports/ccc-100/81377

5 NETL Office of Performance and Benefits group using EIA Outage data, Outage Data - NERC GADS Database 9/19/12 Accessed 1/9/13; http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html

6 EPRI, 1996, TR-106453, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=TR-106453

7 NETL Office of Program Performance and Benefits, 2014 – http://www.netl.doe.gov/research/coal/crosscutting/sensors-controls

8 IEA,2004, Clean Coal Centre, ISBN: 92-9029-395-0, "Upgrading instrumentation and control in coal-fired power plant, CCC/80" http://www.iea-coal.org.uk/reports/ccc-80/81095

9 Nalbandian, 2004 IEA Clean Coal Centre, , CCC/80, ISBN: 92-9029-395-0, http://www.iea-coal.org.uk/reports/ccc-80/81095

10 EPRI, 2006, TR1012694, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001012694

11 H. L. Tuller and S. R. Bishop: Annu. Rev. Material Research, 2011, Vol. 41, pp. 369-98.

12 K. N. Grew and W. K. S. Chiu: J. Power Sources, 2012, Vol. 199, pp. 1-13.

13 S. Zhang and F. Yu: J. American Ceramic Society, 2011, Vol. 94, pp. 3153-3170.

- H. L. Tuller and S. R. Bishop: Annu. Rev. Material Research, 2011, Vol. 41, pp. 369-98.

14 K. N. Grew and W. K. S. Chiu: J. Power Sources, 2012, Vol. 199, pp. 1-13.

- S. Zhang and F. Yu: J. American Ceramic Society, 2011, Vol. 94, pp. 3153-3170.

15 Program on Technology Innovation: Combustion Exhaust Gas Monitoring with Laser Absorption Sensors, EPRI 11-Jul-2012, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001025809

16 steam temperature of 760°C, and steam pressures above 3500 psi at material design life of at least 100,00 hrs at mechanical stress levels of 14,500 psi (100 MPa)

17 Woodhead Publishing Series in Energy Edited by: D. Roddy ISBN: 978-1-84569-515-6 "Advanced Power Plant Materials, Design and Technology" http://www.sciencedirect.com/science/book/9781845695156

18 EPRI 26-Jun-2014, Description of Past Research: Fossil Materials and Repair (Program 87), http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002003364

19 2014 IEA Clean Coal Centre on High temperature steels in pulverised coal technology, CCC/234, CCC/234 - ISBN: 978-92-9029-554-9 http://bookshop.iea-coal.org.uk/reports/ccc-234/83353

20 Guidelines and Specifications for High-Reliability Fossil Power Plants: Recommendations for the Application of Hardfacing Alloys for Elevated-Temperature Service, 24-Mar-2015, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004990

21 "Steam oxidation of fossil power plant materials: collaborative research to enable advanced steam power cycles" A. T. Fry *a; I. G Wright b; N. J Simms c; B. McGhee d; G. R. Holcombe Materials at High Temperature Volume 30, Issue 4 (December 2013), pp. 261-270 DOI: http://dx.doi.org/10.3184/096034013X13809076327729

22 Data Compilation for Grade 91 Steel Creep-Fatigue Datasheets, 12-Jun-2015, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002003260

23 2006 NSF report on simulation-based engineering science describes how simulation can revolutionize engineering http://www.nsf.gov/pubs/reports/sbes_final_report.pdf

24 Carbon Capture Simulation Initiative, https://www.acceleratecarboncapture.org

25 NETL 2014, Open source multiphase flow modeling for real-world applications, https://mfix.netl.doe.gov/mfix/

26 Web Site: "FY 2014 Projects for Improving the Design, Construction, and Operation of Fossil Energy Systems", http://energy.gov/fe/fy-2014-projects-improving-design-construction-and-operation-fossil-energy-systems

27 MacDowell et al., 2015, J. Computer and Chemical Engineering vol74. Pp 169-183, http://dx.doi.org/10.1016/j.compchemeng.2015.01.006

28 Web Site: "FY 2014 Projects for Improving the Design, Construction, and Operation of Fossil Energy Systems", http://energy.gov/fe/fy-2014-projects-improving-design-construction-and-operation-fossil-energy-systems

29 USGS Circular 1405, 2014, Estimated Use of Water in the United States in 2010. U.S. Department of Energy, "The Water-Energy Nexus: Challenges and Opportunities", June 2014, http://www.energy.gov/downloads/water-energy-nexus-challenges-and-opportunities

30 DOE, 2014, Report "The Water-Energy Nexus: Challenges and Opportunities", http://www.energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf

31 Macknick et al., Environ. Res. Lett. 7 (2012) 045802 (10pp)

32 DOE, 2014, Report "The Water-Energy Nexus: Challenges and Opportunities", http://www.energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf

33 Ibid

34 SPX ClearSky Plume Abatement Cooling Tower, http://www.spxclearsky.com/

35 NETL Clean Coal Technology, topical report #27, "Clean Coal Power Initiative, Round 1 Demonstration Projects, Applying Advanced Technologies to Lower Emissions and Improve Efficiency", http://www.netl.doe.gov/File%20Library/Research/Coal/major%20demonstrations/ccpi/lignite/CCT-Topical-Report-27.pdf

36 For other current research activities, see ARPA-E's program on Advanced Research In Dry Cooling (ARID) at http://arpa-e.energy.gov/?q=arpa-e-site-page/view-programs and the NSF-EPRI work on "Water for Energy-Advanced Dry Cooling for Power Plants", http://www.nsf.gov/pubs/2013/nsf13564/nsf13564.htm

37 Patent: EP 2069695 A2, Desalination method and system using a continuous helical slush removal system

38 Lissianski, GE desalination research, http://www.netl.doe.gov/File%20Library/Events/2015/crosscutting/Crosscutting_20150428_Poster23_GE.pdf

39 Li et al., J. Applied Energy, 2014; 116:101–110. DOI: 10.1016 "Combination of CO2 geological storage with deep saline water recovery in western China: Insights from numerical analyses"

Acronyms

CBTL	Coal-biomass to liquids
CCS	Carbon capture and storage, which includes potential co_2 utilization
CLC	Chemical looping combustion
CO_2	Carbon dioxide
COE	Cost of electricity
cP	Centipoise
EOR	Enhanced oil recovery
H_2	Hydrogen
H_2O	Water
HIP/PM	Hot Isostatic Pressure of Powdered Metal
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
MEA	Monoethanolamine
NGCC	Natural gas combined cycle
NOAK	Nth of a kind
NOC	Normal operating conditions
PC	Pulverized coal
RDD&D	Research, development, demonstration, and deployment
ROIP	Residual oil in place
ROZ	Residual oil zone
sCO_2	Supercritical CO_2
SOFC	Solid oxide fuel cell
SOTA	State of the art
USC	Ultra-supercritical