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Assessment on Carbon Capture Technology: A Literature Review

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***Abstract*--The dominance of coal resources in many countries and the advantage of coal to generate power in terms of cost and abundance of energy supply make coal a critical source of energy. As a result, considering the climate change challenges and the carbon dioxide emission problems from coal-fired power plants, make the development of carbon capture and storage technology crucial to reconcile the conflict between carbon dioxide emission mitigation and the need for sufficient energy supply to satisfy the demand. The research objective of this study is to overview the assessment methods of carbon capture technologies and to propose a holistic evaluation model for them.**

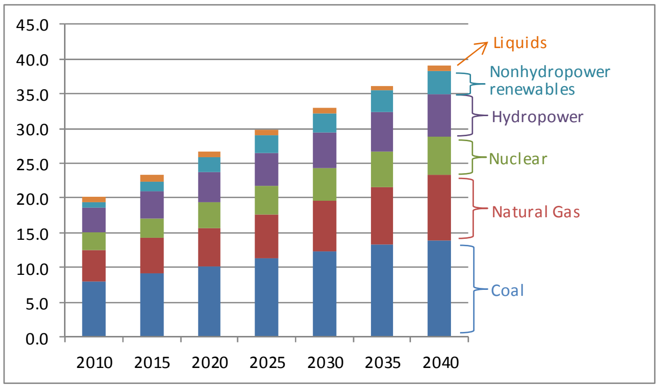
I. INTRODUCTION

With the growing demand of energy consumption, most countries have being using coal as the primary energy source. According to the World Coal Association Coal fact sheets, 41% of world's electricity is generated by coal and 68% of the steel is produced by coal as well [1], [2]. In fact, the forecast for energy consumption growth rates indicates that the growth of coal still surpasses other alternatives according to the Energy Information Administration (EIA) of the United States Department of Energy (DOE). [3] The international outlook released in 2013 by EIA demonstrated that Coal is still leading electricity generation in the near future in Figure 1 [4].

Global warming has been shown to be a threat to leading to extinction of species, an unbalanced ecosystem and health problems for people [5]. The carbon dioxide emission from coal power plants is the main contributor to global warming. A worldwide climate target is to stabilize the global warming of 2°C, as there will be a severe consequence if warming exceeds 2°C [5], [6]. The need for clean technologies to ensure free or near zero carbon dioxide emission is critical. As a result, clean coal technologies are important to maintain a friendly and sustainable environment. Current technologies are capable of capturing up to 90% carbon dioxide to reduce carbon emission [7]. The technology management literature emphasizes that the assessment of technologies is important for both companies and policy makers because of its significant impact on gaining and maintaining competitive advantage in market. [8], [9] Therefore, effective management of these technologies is the major concern by decision makers. [9] Development and evaluation of carbon capture technologies have been continuing for several decades. This paper aims to overview the assessment methods that have been used to evaluate carbon capture technologies and to propose a new, holistic evaluation model.

II. CLEAN COAL

Researchers have been working on making coal as one of the clean energy sources [10]. The abundance of coal reserves makes coal still the primary source of energy to generate electricity compared to others because of its low cost and supply stability [11]. Clean by definition is opposite to dirty. Ideally, if the environmental issues caused by coal power plants can be avoided or eliminated, then coal will be the most reliable clean energy. Therefore clean coal technologies play a significant role in the energy strategy and management. Numerous studies have been conducted on clean coal technologies. The Canadian Clean Power Coalition defines clean coal technologies as "technology that virtually eliminates air and carbon dioxide emissions from coal-fired power plants". [12] The International Energy Agency (IEA) clean coal center refers to clean coal technologies as "those who facilitate the use of coal in an environmentally satisfactory and economically viable way covering emissions, effluents, and residues". [13] The National Mining Association (NMA) describes clean coal technologies as technologies to help reduce the emission of sulfur dioxide and nitrogen oxide from coal combustion. [14] From the cost effectiveness perspective, clean coal technologies are the technologies that make it possible to use coal to generate environmentally friendly power at an acceptable cost. [15]

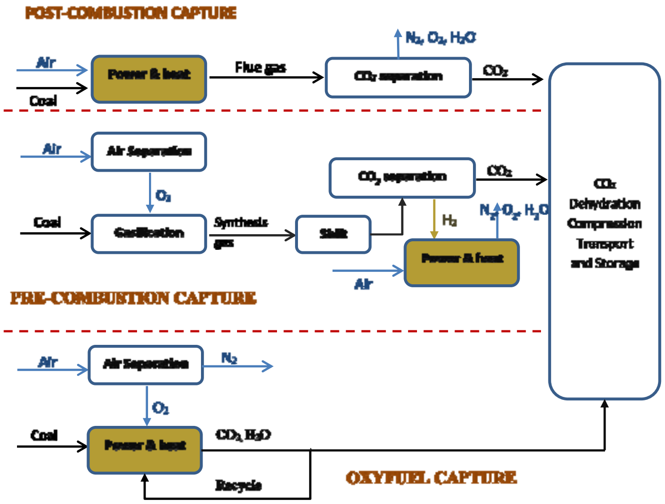


Source: EIA, International Energy Outlook 2013 [4]
Figure 1 World electricity generation by energy source (trillion kilowatthours)

One of the major research areas of clean coal technology is Carbon Capture and Storage (CCS). CO_2 is mainly generated from combustion. Fossil fuel power plants such as coal-fired power plants and natural gas power plants, as well as some industry sectors are the main sources of CO_2 emission. The clean coal process is involved in the coal conversion from pre-combustion to the flu gas cleaning after combustion. For example, unwanted materials and pollutants such as sulfur dioxide and nitrogen oxide can be removed in coal conversion process to increase the combustion efficiency by coal washing and gasification technology. Coal gasification can also be utilized to generate liquid fuel by coal liquefaction. [14], [16], [17] CCS aims to separate and capture CO_2 to prevent CO_2 from emitting to atmosphere by storing it in the safe location. [16], [18]–[20] CCS is considered as the possible option of directly controlling the emission. Analysts estimate the current carbon capture capability is 90% of CO_2 to reduce emission by 20% [16], [21]. According to IEA Energy Technologies Perspective 2008, CCS will contribute the most to the CO_2 emission reduction by 2020 among all power sectors including the renewable sectors [21].

III. CARBON CAPTURE PROCESS

The capture process is categorized into three approaches: post-combustion capture, pre-combustion capture, and oxy-fuel combustion. Figure 2 is the flow chart of three capture approaches. [20], [22]



Source: [20], [22]
Figure 2 Carbon Capture Approaches

Post-combustion capture is to separate CO_2 at the end of the combustion by using solvents. Post-combustion by far is the most mature one among three approaches. It has been developed for 50 years and many power plants already use it to capture CO_2 with the potential of large-scale installation capability. A-major benefit of post-combustion is that it can be used in the existing power plants by retrofitting. [19] The capture system can be installed and deployed in both the coal-fired power plants and the natural gas power plants. [19]

Pre-combustion capture is to convert fuel to the syngas that is the mix of hydrogen and CO_2 before the combustion. This conversion process is known as gasification. The hydrogen then can also be used for transportation and heating source in addition to generating electricity. This approach has better efficiency performance than the post-combustion capture, but it requires building new power plants. [19]

Oxy-fuel combustion is unlike the other two approaches in the sense that it burns fuel in oxygen to produce a flue gas containing CO_2 and water vapor (H_2O) that can be recycled to heat, as well as a small amount of NO_X and SO_X. CO_2 capture is not required after the oxy-fuel combustion, but it has less energy efficiency than the other two approaches due to the need to generate oxygen from air and additional gas treatment system. [19], [21]

IV. CARBON CAPTURE TECHNOLOGIES

Carbon capture can be handled with physical and chemical processes. According to [7], [23]–[25], there are five types of capture methods: absorption, adsorption, membranes, cryogenic, and biotechnologies. Table 1 is the summary of current capture technologies for the three basic approaches grouped by the separation principles by Zahra [24]. The pre-combustion, post-combustion and oxyfuel capture systems all use membranes, solid sorbents and cryogenic methods to separate CO_2. Pre-combustion also uses Alumina in addition to zeolites and activated carbon sorbents methods. Current Oxyfuel capture systems are not based on solvents method, but bio-mimetic solvents are under development for future oxyfuel capture system. In fact, biotechnology is one of CO_2 separation principles under development. [24]

TABLE 1 SUMMARY OF CURRENT CARBON CAPTURE TECHNOLGIES

Capture Method	Pre-combustion	Post-combustion	Oxyfuel
Solvents/Absorption	Chemical solvents	Chemical solvents	
	Physical Solvents		
Membranes	Polymeric	Polymeric	Polymeric
Solid Sorbents	Zeolites	Zeolites	Zeolites
	Activated carbon	Activated carbon	Activated carbon
	Alumina		
Cryogenic	Liquefaction	Liquefaction	Distillation

Source: [24]

V. CURRENT STATUS AND ISSUES

During the combustion of coal in traditional coal power plants, the emission of greenhouse gas including carbon dioxide, methane, and nitrogen oxide has proved to be the main pollutant~~s~~ for global warming. Acid rain caused by other pollutants such as sulfur dioxide is also generated from coal combustion. [26] It is clear that the air pollution is the main driver of the clean technology development. However, the use of coal involves the power producers, energy consumers, power plant equipment suppliers, as well as governments and agencies. IEA refers to them as the coal sectors. To successfully use cleaned coal requires all of these sectors to collaborate together.

The growth of economy is building on energy consumption. There is increasing pressure on power producers to meet the demands of increasing energy consumption. Unfortunately coal capture technologies at current stage are very expensive because of the high cost of retrofitting existing plants and building new power plants. For example, the cost of the FutureGen project that DOE proposed for building a near zero-emission coal fire power plant is estimated to be three times more than a regular coal power plant. [27] For energy consumers including utilities and end users, energy price is their biggest concern. Among many critiques on the use of clean coal technologies, one argument is that consumers may have to face the more expensive electricity bill due to the high cost of power generation. Therefore, reducing the cost has a significant impact on the acceptability of coal capture technologies. [16], [19], [20], [28], [29]

Strong government funding support~~s~~ is needed for the development of clean coal technologies to reduce the generation and operation cost. [27] An on-going debate on clean coal development is whether governments and agencies should encourage the development of clean coal technologies or change the direction to the renewable energy development. Energy supply and efficiency are the two aspects that governments try to secure in addition to the sustainable environment. As a result, energy management strategy plans and decisions will have significant impact on the development of the technology. [30]

VI. TECHNOLOGY MANAGEMENT METHODS

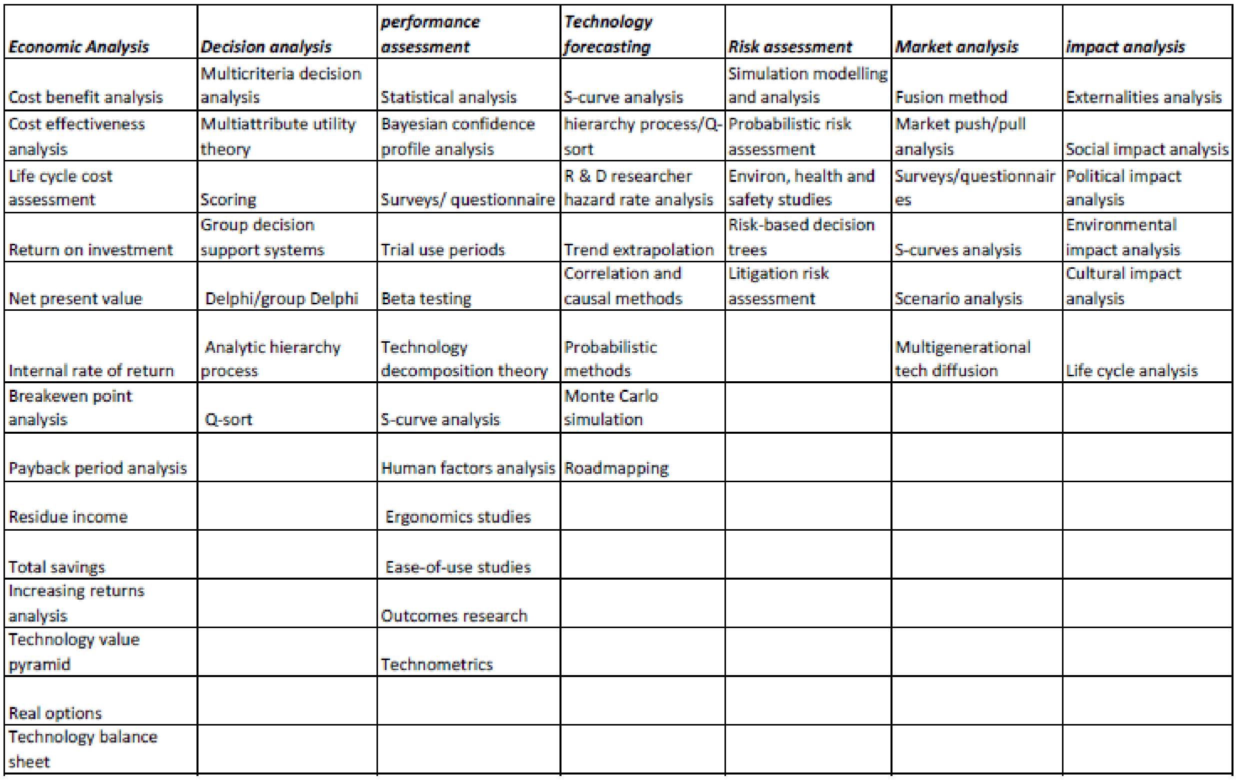
There is a large amount of researches on the assessment and evaluation of technologies. Technology evaluation, technology selection and technology assessment are well-known key words to explore the related literature. In [31], Thien grouped methods and tools that have been applied to technology assessment into two domains: for business and non-governmental uses such as universities and research labs, and for public decision-making. Based on this study, technology assessment methods can measure technologies by technology performance, forecast technologies by road mapping, use scenario analysis for technological planning, consider financial aspects using cost benefit analysis, and conducting impact assessment from social, political and environmental perspectives [31]. The author concluded that integrated, holistic methods from multiple perspectives were often used in public decision-making domain and operational methods are favored by the private sector. Musango and Brent summarized the technology assessment methods and tools in their energy technological systems research following [31] and [8]. The summary in Table 2 included economic analysis, decision analysis, performance assessment, technology forecasting, risk assessment, market analysis, and impact analysis for decision makers. [32] As we can see, though difference methods are used to assess different aspects of a technology, technology assessment has been conducted from various aspects.

A. Multiple Perspectives Approach

Technical, organizational, and personal perspectives (T.O.P) approach was first developed by Harold A. Linstone. [33] Often time the implementation of a new or emerging technology is difficult to accomplish or even not feasible because of the complexity of the real world situations. The concept of multiple perspectives thinking is an important guideline for integrated analysis, adopted and have been applied by many researchers or analysts in building their models to forecast and evaluate technologies.[9], [33]–[35] Socio-technical system analysis is clearly a good application of multiple perspectives approach to fill this gap. Multiple perspectives approach is often used for policy and management decisions in the energy field [35]. Sheikh [36] reviewed the literature of Solar Photovoltaic technology (PV) assessment methods and observed that analysts often use multiple-criteria decision analysis approach to evaluate energy or technology alternatives, such as the analytic hierarchy process (AHP) evaluation method[36], [37]. His application on PV technologies assessment demonstrated the hierarchical decision model (HDM) with social, technological, economic, environmental, and political perspectives (STEEP) is a useful integrated assessment method for the analysis and assessment of energy alternatives.

VII. ASSESSMENT OF CARBON CAPTURE TECHNOLOGIES

Most of the assessment approaches for carbon capture technologies are based on the technical and economic studies. As mentioned earlier, cost reduction and efficiency improvement drive the development of carbon capture and certainly have direct impacts on the adoption of carbon capture technologies. The International Energy Agency (IEA) established the Coal Industry Advisory Board (CIAB) in 1976. CIAB focuses on the variety issues related to the development of coal. In 1996, CIAB conducted a serious study of clean coal technologies to find out what will mostly impact its future by identifying important factors from the survey of industry attitudes. [38] CIAB concluded that the



Economic Analysis	***Decision analysis***	***performance assessment***	***Technology forecasting***	***Risk assessment***	***Market analysis***	***impact analysis***
Cost benefit analysis	Multicriteria decision analysis	Statistical analysis	S-curve analysis	Simulation modelling and analysis	Fusion method	Externalities analysis
Cost effectiveness analysis	Multiattribute utility theory	Bayesian confidence profile analysis	hierarchy process/Q-sort	Probabilistic risk assessment	Market push/pull analysis	Social impact analysis
Life cycle cost assessment	Scoring	Surveys/ questionnaire	R & D researcher hazard rate analysis	Environ, health and safety studies	Surveys/questionnaires	Political impact analysis
Return on investment	Group decision support systems	Trial use periods	Trend extrapolation	Risk-based decision trees	S-curves analysis	Environmental impact analysis
Net present value	Delphi/group Delphi	Beta testing	Correlation and causal methods	Litigation risk assessment	Scenario analysis	Cultural impact analysis
Internal rate of return	Analytic hierarchy process	Technology decomposition theory	Probabilistic methods		Multigenerational tech diffusion	Life cycle analysis
Breakeven point analysis	Q-sort	S-curve analysis	Monte Carlo simulation			
Payback period analysis		Human factors analysis	Roadmapping			
Residue income		Ergonomics studies				
Total savings		Ease-of-use studies				
Increasing returns analysis		Outcomes research				
Technology value pyramid		Technometrics				
Real options						
Technology balance sheet						

Source: [32]

Table 2 Summary of technology assessment methods and tools

choice of clean coal technology could be made by considering maturity of technology, plant size, fuel flexibility, thermal efficiency, operational performance, environmental performance, availability, reliability and maintainability, construction issues, and capital cost. Cost, market acceptance of new technologies, maturity and reliability of the technology, and competition from other energy alternatives are the major barrier to improve the clean coal technology. [38]

The National Energy Technology Laboratory (NETL) under the U.S Department of Energy (DOE) is a major energy research laboratory that supports clean coal studies. The 17 reports released since 2006 provide analysis of carbon capture technologies focusing on cost and performance estimation. [39] Congressional Research Service (CRS) published a technology assessment report of carbon capture in 2013 done by Carnegie Mellon University (CMU), Department of Engineering and Public Policy from engineering-economic perspective based on technology maturity and costs. [19] In this report, the authors simplified the Technology Readiness Levels (TRLs) to assess the maturity of current available carbon capture technologies: Commercial Process Level, Full-Scale Demonstration Plant Level, Pilot Plant Scale Level, Laboratory or Bench Scale Level, and Conceptual Design Level.[19] CMU developed a computer-model to analyze the cost and performance of environmental emission control system at coal-fired power plants for decision makers to assess the related carbon control technologies known as the Integrated Environmental Control Model (IECM) [40]. The two key criteria models were: performance and uncertainty, and cost. The model has been used to assess variety carbon capture technologies. [7], [18], [40], [41]

In addition to the massive technical-economic analysis on technology assessment, there are an increasing number of social science studies on the development of carbon capture and storage technologies. The social influence has been noted in other studies such as those on innovation systems. Technological innovation system is an interdependent network involved with various actors' functions including firms, organizations, institutions, policy sectors. The key concept is the coevolution of these actors associated with technology in the economy[42], [43]. Report [42] defined the US CCS innovation system as seven key functions: entrepreneurial activity, knowledge creation, knowledge diffusion, guidance, market creation, resource mobilization, and legitimization. The system can be used to understand the change of technology and assess its impact on the performance of innovation system. [42]

There are two common research areas in social science studies on carbon capture technology development: public acceptance and understanding towards technology and economic performance or impact of CCS. [44], [45] Nils argued that in addition to the quantitative analysis such as the learning curve models focusing the cost reduction and the learning rates that commonly used in the study of learning and innovation process of CCS, qualitative approach such as the socio-technical analysis is also needed. He developed a new socio-technical framework to assess technologies by considering uncertainty in the CCS innovation system. [43] The framework noted the importance of analyzing the development of CCS technologies based on the co-evolution point of view including technical, economic, financial, political and societal issues and managed to dynamically evaluate the validity and maturity of CCS technology under the interactive influence of these uncertainties. [44]–[46]

VIII. DISCUSSION

The social, technical, environmental, economic, and political perspectives used in the hierarchical decision model provide a holistic approach to evaluate energy related technologies. [35] However, current assessment studies on carbon capture technologies are mainly based on cost and efficiency, technology maturity and uncertainty. Most reports related to coal carbon technologies published in CIAB, IEA, CMU, NETL, and CRS organizations are from the technical and economic perspectives. A few of their studies integrate environmental impact of coal carbon technologies together with technical and economic considerations. IECM developed by CMU includes green gas emission efficiency calculation in the cost model. The uncertainty from the carbon capture innovation system can be used for decision makers to validate the technology and be prepared for any changes technology may face in the future. The socio-technical analysis considers the carbon capture technologies as a whole innovation system and the outcome of the socio-technical framework is the assessment of system performance. Although the political influence is also included in the socio-technical framework, there is no general model to evaluate how social, environmental, and political perspectives impact each other and impact the technical or economic performance of each carbon capture technology, as well as the contribution to the overall performance from each perspective. Therefore, there is a need to develop a holistic model from STEEP perspectives to evaluate carbon capture technology alternatives.

IX. FUTURE RESEARCH

As discussed above, current decision methods cannot be used to quantitatively evaluate the carbon capture technology alternatives from integrated social, technological, economic, environmental, and political perspectives. The research currently underway by the author of this paper aims to define criteria from social, technological, economic, environmental, and political perspectives in order to build a holistic hierarchical decision model for decision makers to evaluate carbon capture technologies. An example of the model is shown below.

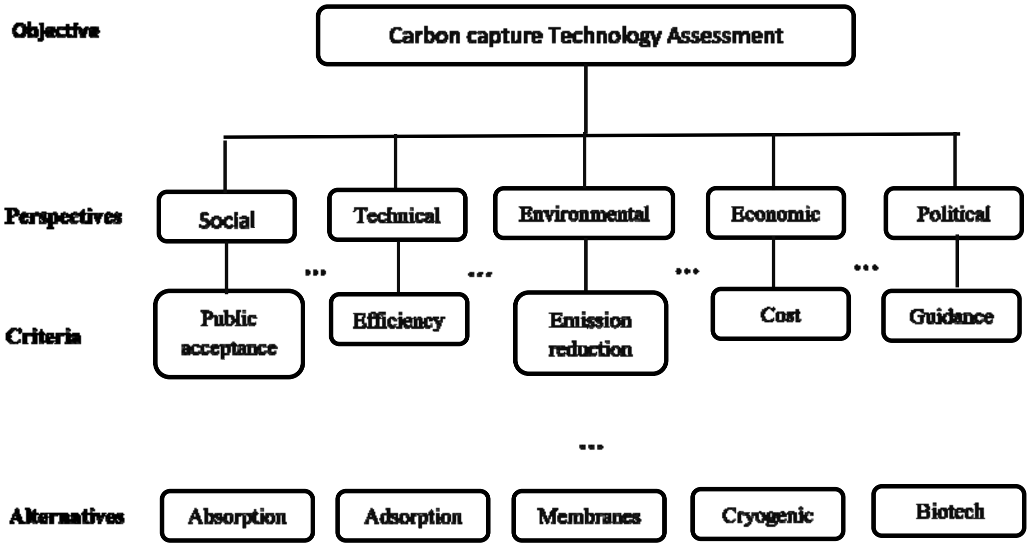


Figure 4 Holistic Carbon Capture Technology Assessment Model

In order to compare the value of technology alternatives based on expert's input, define

$P_k : k = 1,...,k$ as each perspective;

$C_{j,k} : j = 1,...,j$ for $k = 1,...,k$ as relative importance of criteria j with respect to perspective k

$A_i : i = 1,...,i$ as each alternative

$a_i^{j,k}$ as relative importance of alternative i with respect to criteria j under perspective k

$V(A_i)$ as relative value of alternative i $V(A_i)$

Therefore, $V(A_i) = \sum_{k=1}^{k}\sum_{j=1}^{j}\sum_{i=1}^{i} P_k * C_{j,k} * a_i^{j,k}$

X. CONCLUSION

The role of coal in the climate control and energy supply is critical and unlikely replaceable. It is likely that coal will continue to dominate the energy market until renewable energy sources can start producing sufficient and reliable energy. However, carbon dioxide emission from coal burning is proved to be the biggest greenhouse gas contributor to be global warming. Therefore, clean coal seems to be the key to prevent or reduce carbon emission and maintain the balance between energy supply and consumption. Among numerous clean coal technology studies, it is shown that carbon capture and storage is essential for turning coal into a clean source of energy. There are three different stages involved in carbon capture and storage: carbon capture, carbon transportation, and carbon storage. This paper is focused on the carbon capture technologies.

The main contribution in the carbon capture stage is to capture carbon dioxide to achieve the goal of none or near-zero emission. Not only engineers, business executives and policy makers but also social-scientists and innovation system researchers have conducted studies to understand and assess carbon capture technologies for different purposes. However, an overview of these studies and methods indicates that a holistic hierarchical decision model is needed for decision makers to evaluate carbon capture technologies from social, technical, environmental, economic, and political perspectives. This is an on-going research. The criteria and sub-criteria for each perspective are still under development. The details of the STEEP perspectives will be modified and finalized, and expert judgments will be quantified to implement the model for assessment decisions.

REFERENCES

[1] WCA, "Coal Matters," *Word Coal Association*. [Online]. Available: http://www.worldcoal.org/resources/coal-statistics/coal-matters/#cookie_accept.

[2] WCA, "Coal Facts," *Word Coal Association*. [Online]. Available: http://www.worldcoal.org/resources/coal-statistics/.

[3] International Energy Agency, "Clean Coal Technologies-Accelerating Commercial and Policy Drivers for Deployment," OECD Publishing, 2009.

[4] EIA, "International Energy Outlook 2013," *U.S. Energy Information Administration*. [Online]. Available: http://www.eia.gov/forecasts/ieo/.

[5] J. Hansen, P. Kharecha, M. Sato, V. Masson-Delmotte, F. Ackerman, D. J. Beerling, P. J. Hearty, O. Hoegh-Guldberg, S.-L. Hsu, C. Parmesan, J. Rockstrom, E. J. Rohling, J. Sachs, P. Smith, K. Steffen, L. Van Susteren, K. von Schuckmann, and J. C. Zachos, "Assessing 'dangerous climate change': required reduction of carbon emissions to protect young people, future generations and nature.," *PLoS One*, vol. 8, no. 12, p. e81648, Jan. 2013.

[6] S. Randalls, "History of the 2 C climate target," *Wiley Interdiscip. Rev. Clim. Chang.*, vol. 1, no. 4, pp. 598–605, 2010.

[7] A. B. Rao and E. S. Rubin, "A Technical, Economic, and Environmental Assessment of Amine-Based CO 2 Capture Technology for Power Plant Greenhouse Gas Control," *Environ. Sci. Technol.*, vol. 36, no. 20, pp. 4467–4475, Oct. 2002.

[8] A. D. P. Henriksen, "A technology assessment primer for management of technology," *Int. J. Technol. Manag.*, vol. 13, no. 5, pp. 615–638, 1997.

[9] Y.-C. Shen, S.-H. Chang, G. T. R. Lin, and H.-C. Yu, "A hybrid selection model for emerging technology," *Technol. Forecast. Soc. Change*, vol. 77, no. 1, pp. 151–166, 2010.

[10] EurActiv, "Coal: a clean energy source for the future?," 2007. [Online]. Available: http://www.euractiv.com/energy/coal-clean-energy-source-future-linksdossier-188387.

[11] K. Mogi, "Challenges for Diffusion of Japan's Clean Coal Technologies," *IEEJ*, 2012. [Online]. Available: https://eneken.ieej.or.jp/data/4326.pdf.

[12] M. Raynolds, "Clean Coal by What Definition?," *Calgary Herald*, 2006. [Online]. Available: http://www.pembina.org/op-ed/1222.

[13] IEA Clean Coal Centre, "Clean Coal Technologies." [Online]. Available: http://www.iea-coal.org/site/2010/database-section/clean-coal-technologies.

[14] NMA, "Backgrounder on Clean Coal Technologyt," *The National Mining Association*. [Online]. Available: http://www.nma.org/pdf/fact_sheets/cct.pdf.

[15] CAER, "Understanding Clean Coal Technologies," *The University of Kentucky Center for Applied Energy Research*. [Online]. Available: http://www.caer.uky.edu/cct/ccthome.html.

[16] R. S. Haszeldine, "Carbon capture and storage: how green can black be?," *Science*, vol. 325, no. 5948, pp. 1647–52, Sep. 2009.

[17] M. Lloyd and J. Blows, "Clean coal technologies: Where does Australia stand?" [Online]. Available: http://www.griffithhack.com.au/Assets/1672/1/GH_CleanCoal_April_2009.PDF.

[18] C. Chen, "A Technical and Economic Assessment of CO2 Captrue Technology for IGCC Power Plants," Carnegie Mellon University, Pittsburgh, PA, 2005, 2005.

[19] P. Folger, "Carbon Capture: A Technology Assessment," 2010.

[20] J. Gibbins and H. Chalmers, "Carbon capture and storage," *Energy Policy*, vol. 36, no. 12, pp. 4317–4322, Dec. 2008.

[21] CCSA, "Carbon Capture & Storage: A crucial technology in addressing climate change," *Carbon Capture & Storage Association*. [Online]. Available: http://www.ccsassociation.org/press-centre/reports-and-publications/.

[22] encapco$_2$, "Precombustion Decarbonisation Technologies," *Enhanced Capture of CO$_2$*. Available: http://www.encapco2.org/technoPDT.htm.

[23] IPCC, "Carbon Dioxide Capture and Storage special report." [Online]. Available: https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf.

[24] M. A. Zahra, "CARBON CAPTURE TECHNOLOGIES OVERVIEW, ASSESSMENT AND POTENTIAL DEVELOPMENT AND DEPLOYMENT IN THE ESCWA REGION," 2013.

[25] W. Hermann, P. Bosshard, E. Hung, R. Hunt, and A. J. Simon, "An assessment of carbon capture technology and research opportunities," *Glob. Clim. Energy Proj. Spring*, 2005.

[26] WCA, “Coal Use & the Environment,” *Word Coal Association*. [Online]. Available: http://www.worldcoal.org/coal-the-environment/coal-use-the-environment/.

[27] Thomas White International, “The Green Report - Is Clean Coal Technology a viable energy alternative?,” *Thomas White International*, 2010. [Online]. Available: http://www.thomaswhite.com/global-perspectives/is-clean-coal-technology-a-viable-energy-alternative/.

[28] M. FInkenrath, “Cost and performance of carbon dioxide capture from power generation,” 2011.

[29] IEA, “Technology Roadmap: Carbon Capture and Storage,” *IEA*, 2013. [Online]. Available: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf.

[30] GBN, “Energy Strategy for the Road Ahead,” *Global Business Network*. 2007.

[31] T. A. Tran and T. Daim, “A taxonomic review of methods and tools applied in technology assessment,” *Technol. Forecast. Soc. Change*, vol. 75, no. 9, pp. 1396–1405, 2008.

[32] J. K. Musango and A. C. Brent, “Assessing the sustainability of energy technological systems in Southern Africa: A review and way forward,” *Technol. Soc.*, vol. 33, no. 1, pp. 145–155, 2011.

[33] H. A. Linstone, *Decision making for technology executives: using multiple perspectives to improved performance*. Artech House Boston, 1999.

[34] H. A. Linstone, “Multiple perspectives: concept, applications, and user guidelines,” *Syst. Pract.*, vol. 2, no. 3, pp. 307–331, 1989.

[35] N. Sheikh, T. Daim, and D. F. Kocaoglu, “Use of multiple perspectives and decision modeling for PV technology assessment.” pp. 1–21, 2011.

[36] N. Sheikh and D. F. Kocaoglu, “A comprehensive assessment of solar photovoltaic technologies: literature review,” in *Technology Management in the Energy Smart World (PICMET), 2011 Proceedings of PICMET’11:*, 2011, pp. 1–11.

[37] H. H. Chen and S. Chen, “The Conceptual Model for the Strategic Planning of Energy Sources,” *Energy Sources, Part B Econ. Planning, Policy*, vol. 9, no. 3, pp. 248–255, 2014.

[38] I. E. A. C. I. A. Board, O. for Economic Co-operation, and Development, *Factors affecting the take-up of clean coal technologies: overview report*. International Energy Agency, 1996.

[39] NETL, “Coal Capture-System Analysis.” [Online]. Available: http://www.netl.doe.gov/research/coal/carbon-capture/analysis.

[40] E. S. Rubin, M. Berkenpas, and K. Kietzke, “Integrated Environmental Control Model,” *Cent. Energy Environ. Stud. Carnegie Mellon Univ. Pittsburgh*, 2010.

[41] H. Zhai and E. S. Rubin, “Techno-economic assessment of polymer membrane systems for postcombustion carbon capture at coal-fired power plants.,” *Environ. Sci. Technol.*, vol. 47, no. 6, pp. 3006–14, Mar. 2013.

[42] M. Hekkert and S. Negro, “Understanding technological change-explanation of different perspectives on innovation and technological change,” *Utrecht University*. [Online]. Available: http://www.innovation-system.net/wp-content/uploads/2013/03/UU_01rapport_uUnderstanding_Technological_Change.pdf.

[43] K. Van Alphen, P. M. Noothout, M. P. Hekkert, and W. C. Turkenburg, “Evaluating the development of carbon capture and storage technologies in the United States,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 971–986, 2010.

[44] N. Markusson, F. Kern, and J. Watson, “Assessing CCS viability-A socio-technical framework,” *Energy Procedia*, vol. 4, pp. 5744–5751, 2011.

[45] N. Markusson, F. Kern, J. Watson, S. Arapostathis, H. Chalmers, N. Ghaleigh, P. Heptonstall, P. Pearson, D. Rossati, and S. Russell, “A socio-technical framework for assessing the viability of carbon capture and storage technology,” *Technological Forecasting and Social Change*. Elsevier, 01-Jun-2012.

[46] N. Markusson and H. Chalmers, “Characterising CCS learning: The role of quantitative methods and alternative approaches,” *Technol. Forecast. Soc. Change*, vol. 80, no. 7, pp. 1409–1417, 2013.