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Overview of Carbon Reduction, Capture, Utilization and Storage: Development of New Framework

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Carbon capture and storage (CCS) is one of the provisional technologies to mitigate the rise of greenhouse gases emission which comes from carbon dioxide (CO_2) emission. The growth and development of CCS technology leads to existence of carbon capture, utilization and storage (CCUS) technologies due to immature technologies of CO_2 storage. Criticality of carbon reduction attracts researchers to study the efficiency of implementing CCS and CCUS latest technologies with economic and environmental goals. This paper discusses the overview of the technologies and the work done by researchers on strategies of implementation of CCS and CCUS. This paper also focuses on the optimal planning of CCS and CCUS technologies. A new framework for carbon reduction, capture, utilization and storage (CARSUS) is introduced for future development. CARCUS is expected to present the best route for carbon dioxide avoidance.

1. Introduction

It is generally known that global warming is the major contributor to the environmental threat in this twentieth century. Studies have shown that global warming is caused by the emission of the greenhouse gases (GHG) linked to the human activities which may result in catastrophic impact if not being controlled and mitigated. GHG emission increment is driven by economic and population growth which are getting higher. This has led to the increase of atmospheric concentration of the six greenhouse gases which are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC's), perfluorocarbons (PFC's) and sulfur hexafluoride (SF_6) (IPCC, 2014). The major contributor of GHG is CO_2 and almost 30 billion t of CO_2 that enters atmosphere was due to human activities each year (Goodall, 2007). The increase in CO_2 has contributed about 76 % of the global greenhouse gases up to 2010 (IPCC, 2014). The intensity of concern and range of viewpoints among the earth's nation are showed through national mitigation and intergovernmental mechanisms such as the United Nations Framework Convention on Climate Change (UNFCCC), a nonbinding agreement aimed at reducing atmospheric concentrations of GHG. In 2009, Prime Minister of Malaysia announced in COP16 that Malaysia has adopted a voluntary indicator to reduce GHG emission intensity of Gross Domestic Product (GDP) by up to 40 % compared to an intensity level of 2005 by 2020. However as discovered that 33 % of reduction is achieved by 2015 hence higher target was set which is 45 % by 2030. This ambitious target is essential for Malaysia since the country was one of the highest contributors to GHG emission among other Asian countries after Singapore and Brunei. Emission of CO_2 can be divided into two categories: stationaries or non-stationary. Stationary sources are a point of large CO_2 emission which provides significant and realistic chances for reduction of CO_2 emission. The large stationary sources are mostly from heavy industries such as power plants, cement production, iron and steel industries, refineries, petrochemicals and gas processing plants which contribute to more than 60 % of the total stationary emission (Hasan et al., 2015). Without further initiative on the emission reduction, the total CO_2 emission from industrial may project up to 90 % by 2050 compared to 2007 (IEA, 2010).
In view of this situation, carbon capture, utilization and storage (CCUS) technology has promising values but there are many drawbacks in economic and environmental term. CCUS technology scheme is basically capturing or collects the CO_2 emitted from industrial, and transported to the location where it can be utilized or being stored underground reservoirs for sequestration (Styring et al., 2011). Selection of the right technology for the right sources is crucial in order to ensure that the implementation of CCUS is cost effective. Therefore

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this paper discusses the strategy of implementation of CCUS, which also focus on the reduction of emission from early stage. This paper also discusses the available techniques and strategies done by researchers in scope of CCS and CCUS.

2. Overview of Carbon Reduction, Capture, Utilization and Storage.

2.1 Carbon dioxide sources

According to EPA (2016) human activities that caused CO_2 emission are mainly from combustion of fossil fuel for energy generation and transportation followed by industrial processes and land use changes. The mix and contribution percentage can be clearly seen from the pie chart in Figure 1. The emission sources stated by EPA (2016) are focusing on CO_2 emission in United State while in Malaysia, Safaai et al. (2010) discussed in his studies that CO_2 emission sources are from the same sectors and projected at similar trend where electricity generation discharged largest amount of CO_2 at 43.35 % as coal is the main fuel combustion. Transportation sector contributes 30.25 % of emission while industrial sector is 26.26 % followed by 0.03 % from residential sector. Total emissions from the four sectors were 88.97 million t and expected to increase by 2020 if no control action taken place (Safaai et al., 2010). Industrial sector can be further distributed into iron and steel, cement, chemical feedstock which contributes the largest percentage of emission in the sector. Figure 2 shows the percentage of emission from industrial sector.

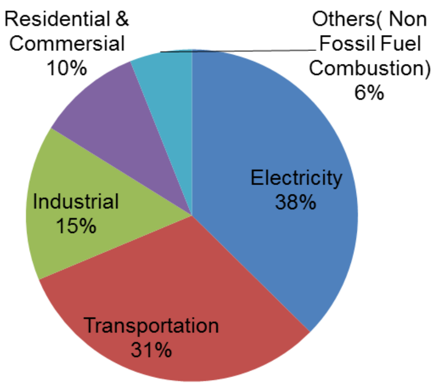

Figure 1: Percentage of emission contribution according to sectors (EPA, 2016)

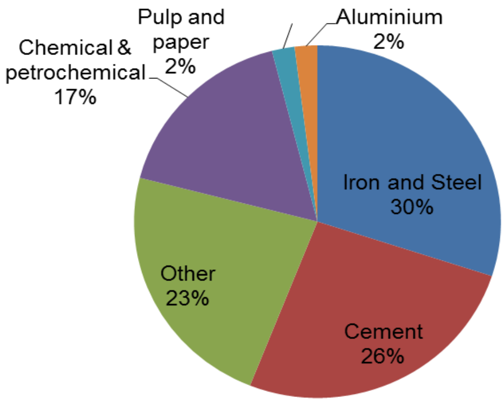

Figure 2: Total direct CO_2 emission from industry (Brown et al., 2012)

2.2 Carbon Reduction strategy

Studies on the reduction of CO_2 may have been done earlier, but only few have been taken in consideration and most of the strategies are still in research stage as the measure on cost effective efficiency remain unrealized (Brown et al., 2012). The reduction of emission at the early stage can also be addressed as mitigation strategies which mainly focus on the improvement of the processes, equipment and procedures (Thomas, 2001). Brown et al. (2012) reviewed the processes which need to be assessed in industrial sector in order to put the abatement potential into realization. Table 1 summarizes the reduction strategies as highlighted by Brown et al. (2012).

Table 1: Emission abatement strategies for industrial sector

Industry	Process Specific Energy Efficient Technologies
Iron and steel	• Switching to more efficient processing routes such as phasing out open hearth furnaces and increased use of scrap with electric arc furnaces • Increased recovery of gases and heat integration from the blast furnace and basic oxygen furnace • Adoption of efficient methods for finishing the final crude steel product
Chemical	• Adoption of best practice reactor designs and processes with best practice heat integration and energy recovery • Design of new catalysts to increase yield and selectivity of desired products • Design and development of novel membrane separation technologies.

Besides industrial sector, deployment of energy efficient power plant is critical for realization of CCS technology as the costing and energy intensity for capturing, transporting and utilization is relatively high. Efficiency improvement for power station is crucial and seem to have significant potential to reduce coal consumption as well as reducing CO_2 emissions (IEA, 2014). IEA (2014) also reported in one of their technical project report, the literature carried search carried out by National Energy Technology Laboratory (NETL) of US Department of Energy (US DOE) on efficiency improvements that could potentially be made by coal fired power plant.

2.3 Carbon Capture technologies

The application of carbon capture storage at large scale of commercial fossil fuel power generation facility is not wide up until mid-2013. Although the components of integrated CCS system are existed and ready for application, CCS has only been used by hydrocarbon exploration, production, and transport, as well as the petrochemical refining sectors (IPCC, 2014). According to IPCC (2014) the largest market for CCS system is most likely found in the power sector where the cost of deploying CCS system will increase. Some concept of CCS technology may already been implemented in other industries where the purpose is not to reduce CO_2 emission. The basic concept of CCS technology in term of power plant is to capture the CO_2 emitted from the burning process. Combustion process will generate fuel gases which consist of variety of gaseous mainly CO_2, H_2O and N_2. Besides these main gaseous, challenge of the system is also to separate from other gaseous such as NO_X, SO_2 and many others. The main CO_2 capture technologies are absorption, adsorption, cryogenics, and membranes (Siikavirta et al., 2002). To date, CO_2 capture technology can be divided into four categories which are post combustion, pre-combustion, oxygen fuel combustion and chemical looping combustion (Spigarelli and Kawatra, 2013). Post combustion capture CO_2 after fuel combustion, pre-combustion capture CO_2 by gasifying the fuel to create high pressure gas stream before combustion, oxy combustion capturing co2 after combustion with oxygen rich atmosphere while chemical looping combustion (CLC) works by using oxygen carrier normally metal oxides to deliver oxygen needed for combustion. Out of all technologies listed, post combustion has the greatest potential while CLC is behind in development and deployment.

2.4 Carbon Utilisation

Carbon utilization is the next step of reducing CO_2 content in atmosphere taking the carbon from the source to sinking route. It also acts as an alternative route instead of directly transport the gas to storage. The existence of carbon utilization differs from CCS here carbon utilisation allows commercialization of emitted CO_2 into valuable products while CCS alone only plays a role on the abatement of CO_2 (Styring et al., 2011).As an alternative to storage, the commercial products can directly be utilized in food and drink industry such as carbonated drinks. Besides that, in oil and gas industry by CO_2 can be utilized by injecting CO_2 at the oil reservoir to enhance oil recovery (EOR).While providing storage solution for CO_2 emission, CO_2-EOR also helps to increase domestic crude oil production (Ferguson et al., 2009). Huang and Tan (2014) reviewed on the existing and under development CO_2 utilization technologies specifically on direct utilization and chemical conversion of CO_2. Based on their review, it is found that researchers are attracted to direct utilization of captured CO_2 via microalgae but the industrial application of microalgae biotechnology in full scale has not been applied yet. Opportunities for utilization of CO_2 are also seen in few other areas such as chemical conversion, mineral carbonation, and biofuel from algae (Styring et al., 2011). In addition, catalytic chemical transformation, electrochemical, thermal and photochemical conversions offer a high value product with industrial potential. Encouraging progress has been achieved in photocatalytic conversion of CO_2 and water vapour into hydrocarbon fuels using sunlight. However, enhancement of conversion rate is necessary and research on the design of co-catalyst is also required to improve selectivity of the product. Large scale, high temperature co-electrolysis of CO_2 and steam has a great utilisation potential but understanding on the reaction occurring in a cell, advances in electrode materials, types of electrolyte is required to reduce cost and improve performance (Styring et al, 2011).

3. Current development of Carbon Capture and Utilisation implementation

The main concern of this paper is on the planning of implementation of the CCS and CCUS. Planning in term of CCS and CCUS refers to the development of a method or strategy in order to achieve the main target which is to reduce CO_2 emission. In order to achieve the target, it is important to ensure that the technologies chosen at each process (capture, utilization and storage) are optimal. Considerable amount of researchers studied on the methods of implementing CCS and CCUS. Middleton and Bielicki (2009a) developed a scalable infrastructure model for CCS (SimCCS) which optimally determined the location of sources and location of CO_2 can be stored. Mixed integer linear programming (MILP) is used for the SimCCS model and solved using ILOG'S CPLEX 11.0. However SimCCS model focused significantly on the optimization of pipeline network. The planning of deployment of CCS also been studied by Lee et al. (2014) which simultaneously considered the grid power implication and source-sink matching using MILP model. The model is done based on retrofit power plant studied by Tan et al. (2010). Roh et al. (2016) developed a systematic method for CO_2 utilization which involves three main stages. The first stage is process synthesis, next is process design and analysis, and, the last stage is innovative and sustainable design. This methodology was adopted from Babi et al. (2015) which originally developed for optimization of chemical production process. On the other hand, Hasan et al. (2015) developed a multi-scale framework for CCUS to minimize the cost while reducing stationary CO_2 emissions in the United States. The studies have shown that more than 3 % of total stationary CO_2 emission in the United States can be eliminated by CCU network. Table 2 summarized of work done by researchers related to carbon reduction, capture, utilization and storage.

Table 2: Summary of previous work related to carbon capture, utilization and storage

Author	Description	Boundaries
Milani et al. (2015)	• A model-based analysis of CO_2 utilization in methanol synthesis plant • Developed a comprehensive model for CO_2 integration in natural gas-based methanol synthesis plant.	• Carbon capture • Carbon utilization
Korkmaz et al. (2009)	• Analysis of retrofitting coal-fired power plants with CO_2 capture • The integration of an amine-based flue gas scrubber with a coal-fired power plant including compression of CO_2 and the resulting effects of the integration on the power plant's operation	• Carbon capture
Middleton and Bielicki (2009b)	• Optimization model that comprehensively models CCS infrastructure, from source -to-sink which able to link sources and reservoirs using a realistic and capacitated pipeline network	• Carbon capture • Network
Oh et al. (2016)	• Energy minimization of Monoethanolamine (MEA)-based CO_2 capture process • Developed a new superstructure for the optimization of CO_2 capture processes	• Carbon capture
Harkin et al. (2012)	• Developed a model that minimize the cost of electricity and maximize the CO_2 capture rate of CCS in power plant. • Combined simulation, automated heat integration and multi-objective optimization	• CCS
Nawi et al. (2016)	• Developed a systematic methodology to reduce CO_2 emission in industry in the form of graphical visualisation tool for cost-effective CO_2 emission reduction strategies	• Reduction
Mirzaesmaeeli et al. (2010)	• Developed a MILP model for power generation planning of electrical system with objective of mitigating pollutant and getting optimal mix of energy supply.	• Reduction
Othman et al. (2009)	• Reviewed on strategic planning on carbon capture from coal fired plants in Malaysia and Indonesia	• Carbon capture
Hasan et al. (2015)	• Developed a multi-scale framework for CCUS to minimize the cost while reducing stationary CO_2 emissions in the United States	• CCUS
Kongpanna et al. (2016)	• Developed a systematic computer-aided framework for sustainable process design is presented together with its application to the synthesis and generation of processing networks for dimethyl carbonate (DMC) production with CO_2 utilization.	• CCUS
Sanpasertparnich and Aroonwilas (2009)	• Determined an optimal design and operating conditions that would offer the maximum power plant efficiency of both subcritical and supercritical pulverized coal-fired power plants.	• Power plant • CCS

4. Carbon reduction, Capture and Utilization and Storage implementation framework for future recommendation

Research efforts on CCUS area is growing and the technologies are systematically developing. It can be seen from previous section that optimal planning on optimization of carbon capture and storage been studied by few researchers. However, inclusion of reducing the carbon emission before capturing in the planning stage has not been significantly studied by any. Therefore, for future direction of CCUS technologies, a framework of carbon reducing, capture, utilization and storage carbon dioxide (CARCUS) is proposed. The inclusion of carbon reduction in the framework of CCUS may reduce the capital cost of capture since the emission is reduced earlier and smaller scale of equipment can be installed. It is important to mention that the proposed CARCUS heuristic could provide a clear route and optimal planning to upgrade the status of CCUS especially in Malaysia. This study will develop MILP with application of GAMS software which would be beneficial for future researcher as this method is reliable & expandable. The result of this study is expected to show the best technologies to be implements by each stage of carbon reduction, capture, utilization and storage hence contributes to the reduction of carbon dioxide emission. In addition, CARCUS allows fossil fuels, such as coal and natural gas, to remain part of our energy mix, by limiting the emissions from their use. Figure 3 shows the workflow of the CARCUS model.

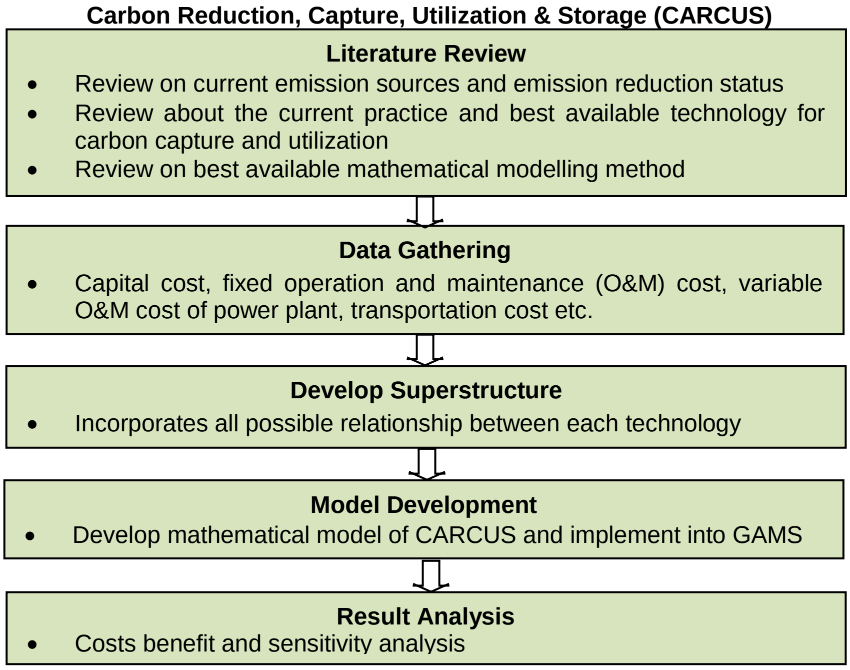

Figure 3: CARCUS research workflow

5. Conclusions

The first part of this paper provides brief idea on CCUS. CCUS technologies available in the market are normally expensive and high energy intensity. Therefore, the implementation and realization of the technologies will not takes place without proper planning due to the drawbacks of the technologies. With respect to the concern of increasing carbon dioxide emission, planning of CCS and CCUS aiming on economic and environmental benefit. This paper also reviewed on the current development of CCS and CCUS in term of optimal planning which are studied and highlighted by researches. A new framework which is CARCUS is suggested to reduce CO_2 emission with inclusion of reduction strategy to the CCUS technology.

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Reference

Babi D.K., Holtbruegge J., Lutze P., Gorak A., Woodley J.M., Gani R., 2015, Sustainable Process Synthesis-Intensification. Computer Chemical Engineering 81, 218-44

Brown T., Florin N., Fennell P., 2012, Reducing CO2 emissions from heavy industry: a review of technologies and considerations for policy makers, Grantham Institute for Climate Change Briefing Papers 7, 32.

Environmental Protection Agency (EPA), 2016, Q & A : EPA Regulation of Greenhouse Gas Emissions from Existing Power Plants (February), 1–8.

Ferguson R.C., Nichols C., Leeuwen T. Van, Kuuskraa V.A., 2009, Storing CO2 with Enhanced Oil Recovery, Energy Procedia 1 (1),.1989–1996.

Goodal C., 2007, How to live a low carbon life: The individual’s guide to stopping climate change, United Kingdom.

Harkin T., Hoadley A., Hooper B., 2012, Using multi-objective optimisation in the design of CO2 capture systems for retrofit to coal power stations, Energy 41 (1), 228–235.

Hasan M.M.F., First E.L., Boukouvala F., Floudas C.A., 2015, A multi-scale framework for CO2 capture, utilization, and sequestration: CCUS and CCU, Computers and Chemical Engineering 81, 2–21.

Huang C.H., Tan C.S., 2014, A review: CO2 utilization, Aerosol and Air Quality Research 14 (2), 480–499.

IEA (International Energy Agency), 2010, Energy Technology perspectives: Scenarios and strategies to 2050, Paris.

IEA (International Energy Agency), 2014, Emissions Reduction through Upgrade of Coal-Fired Power Plants.

Kongpanna P., Babi D.K., Pavarajarn V., Assabumrungrat S., Gani R., 2016, Systematic methods and tools for design of sustainable chemical processes for CO2 utilization, Computers and Chemical Engineering 87, 125–144.

Korkmaz Ö.̈, Oeljeklaus G., Görner K., 2009, Analysis of retrofitting coal-fired power plants with carbon dioxide capture, Energy Procedia 1 (1), 1289–1295.

Lee J.Y., Tan R.R., Chen C.L., 2014, A unified model for the deployment of carbon capture and storage, Applied Energy 121, 140–148.

Middleton R.S., Bielicki J.M., 2009a, A scalable infrastructure model for carbon capture and storage: SimCCS, Energy Policy 37 (3), 1052–1060.

Middleton R.S., Bielicki J.M., 2009b, A comprehensive carbon capture and storage infrastructure model, Energy Procedia 1 (1), 1611–1616.

Milani D., Khalilpour R., Zahedi G., Abbas A., 2015, A model-based analysis of CO2 utilization in methanol synthesis plant, Biochemical Pharmacology 10, 12–22.

Mirzaesmaeeli H., Elkamel A., Douglas P.L., Croiset E., Gupta M., 2010, A multi-period optimization model for energy planning with CO2 emission consideration, Journal of Environmental Management 91 (5), 1063–1070.

Nawi W.N.R.M., Alwi S.R.W., Manan Z.A., Klemes J.J., 2016, A systematic technique for cost-effective CO2 emission reduction in process plants, Clean Technologies and Environmental Policy 8 (6), 1769–1777.

Oh S., Binns M., Choa H., Kim J.K., 2016, Energy minimization of MEA-based CO2 capture process, Applied Energy 169, 353–362.

Othman M.R., Zakaria R., Fernando W.J.N., 2009, Strategic planning on carbon capture from coal fired plants in Malaysia and Indonesia: A review, Energy Policy 37 (5), 1718–1735.

Roh K., Frauzem R., Nguyen T.B.H., Gani R., Lee J.H., 2016, A methodology for the sustainable design and implementation strategy of CO2 utilization processes, Computers and Chemical Engineering 91, 407–421.

Safaai N.S.M., Noor Z., Hashim H., Ujang Z., 2010, Projection of CO2 Emissions in Malaysia, Environmental Progress & Sustainable Energy 30 (4), 658–665.

Sanpasertparnich T., Aroonwilas A., 2009, Simulation and optimization of coal-fired power plants, Energy Procedia 1 (1), 3851–3858.

Styring P., Jansen D., de Coninck H., Reith H., Armstrong K., 2011, Carbon Capture and Utilisation in the green economy, The Centre for Low Carbon Futures, York, UK.

Tan R.R., Ng D.K.S., Foo D.C.Y., Aviso K.B., 2010, Crisp and fuzzy integer programming models for optimal carbon sequestration retrofit in the power sector, Chemical Engineering Research and Design 88 (12), 1580–1588.

Thomas D.C., 2001, Carbon Dioxide Mitigation: A Challenge for the Twenty-First Century, National Academies Press,Bethesda, USA