Energy Policy xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Achieving 80% greenhouse gas reduction target in Saudi Arabia under low and medium oil prices

Yousef M. Alshammari*, S. Mani Sarathy

*Clean Combustion Research Center, 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*

ARTICLE INFO

*Keywords:*
$CO_2$ emissions
Decarbonisation scenarios
Power generation
Oil breakeven price
Saudi Arabia

ABSTRACT

COP 21 led to a global agreement to limit the earth's rising temperature to less than 2 °C. This will require countries to act upon climate change and achieve a significant reduction in their greenhouse gas emissions which will play a pivotal role in shaping future energy systems. Saudi Arabia is the World's largest exporter of crude oil, and the 11th largest $CO_2$ emitter. Understanding the Kingdom's role in global greenhouse gas reduction is critical in shaping the future of fossil fuels. Hence, this work presents an optimisation study to understand how Saudi Arabia can meet the $CO_2$ reduction targets to achieve the 80% reduction in the power generation sector. It is found that the implementation of energy efficiency measures is necessary to enable meeting the 80% target, and it would also lower costs of transition to low carbon energy system while maintaining cleaner use of hydrocarbons with CCS. Setting very deep GHG reduction targets may be economically uncompetitive in consideration of the energy supply requirements. In addition, we determine the breakeven price of crude oil needed to make CCS economically viable. Results show important dimension for pricing $CO_2$ and the role of CCS compared with alternative sources of energy.

## 1. Introduction

COP 21 resulted in a global agreement that more than 100 countries have adopted an agreement to limit the earth's temperature by not more than 2 °C (Meinshausen et al., 2009; Krewitt et al., 2007). Carbon capture and storage (CCS) is expected to lead the global efforts of reducing $CO_2$ emissions from power generation sectors (Riahi et al., 2004). Research on the technological pathways to achieve deep reductions in greenhouse gas (GHG) emissions has been active over the past years in both power generation and transport sectors at a period of high oil prices above $100/bbl (Damen et al., 2009; Holtz et al., 2001; Kay et al., 2014; Leighty et al., 2012; McCollum et al., 2012; McCoy and Rubin, 2009; Mustapa and Hussain, 2016; van den Broek et al., 2008; Yang et al., 2009, 2015; Williams et al., 2012; Hourcade and Robinson, 1996; Richels and Sturm, 1996; Jaccard and Montgomery, 1996; Melaina and Webster, 2011; Taylor et al., 2010; Lai et al., 2012; McCollum and Yang, 2009; Riahi et al., 2004). For instance, Riahi et al. (2004a, 2004b) showed that the technological improvements in CCS technology can be a critical factor in shaping the future of low carbon energy systems based upon the utilisation of fossil fuels. They further showed that IGCC and NGCC can be an attractive and cost effective option for the integration of CCS on the long run. Yang et al. (2015) showed that 74% reduction in California's GHG emissions can be achieved across all reduction scenarios and the use of CCS with biofuels enables negative emissions. Their results show that major energy system transformation is required to meet the 80% reduction target. Williams et al. (2012) showed that the energy system transformation to achieve the 80% reduction target would require the use of technologies that are not yet commercially available with expected major role of electricity and energy efficiency. van den Broek et al. (2008) showed planning of future electricity mix using CCS, nuclear and renewable sources of energy in the Netherlands. They showed that if nuclear energy is excluded as a mitigation option, CCS can be cost-effective to avoid 29 MTon in 2020 in the Dutch electricity sector. Another study for scenarios of GHG reduction was conducted for China power generation sector (Cai et al., 2007) which showed nuclear and hydropower can be an important GHG mitigation option on the long run. They also highlighted that CCS and solar thermal could become cost-competitive in emission reduction after 2030. Other scenario analysis studies on greenhouse reduction in China (C. Wang et al., 2007; K. Wang et al., 2007; Cai et al., 2008) showed mitigation measures in China electricity sector, iron and steel and transport sectors reporting important cost estimation for climate policy makers to consider to devising future $CO_2$ reduction policies. The costs of $CO_2$ avoidance has been the subject of investigation by many studies (van den Broek et al., 2008; Yang et al., 2015; Hourcade and Robinson,

* Corresponding author.
*E-mail address:* yousef.alshammari08@alumni.imperial.ac.uk (Y.M. Alshammari).

http://dx.doi.org/10.1016/j.enpol.2016.10.027
Received 17 April 2016; Received in revised form 1 October 2016; Accepted 19 October 2016
Available online xxxx

1996; Richels and Sturm, 1996; Jaccard and Montgomery, 1996; Tol, 1999). For instance, Hourcade and Robinson (1996) reported that that estimates of the GHG mitigation costs depends critically on policy decisions, and assumptions, expectations, and social and technological developments. Costs of $CO_2$ avoidance in different countries were reported by different researchers to be between €30/Ton$CO_2$ to €50/Ton$CO_2$ (van den Broek et al., 2008), \$12/Ton$CO_2$ to \$14/Ton$CO_2$ (Cai et al., 2008), \$9/Ton$CO_2$ to \$124/Ton$CO_2$ by (Yang et al., 2015), \$49.7/Ton$CO_2$ to \$62.6/Ton$CO_2$ (Rubin et al., 2007), and 18–72/Ton $CO_2$ (Wilson, 1992; Herzog, 1999; Hendriks et al., 2000; David and Herzog, 2000).

Coupling CCS with enhanced oil recovery (EOR), when analysing transition to low carbon scenarios, is an important strategy to improve the cost-benefits of $CO_2$ avoidance (Mansouri et al., 2013; Liu et al., 2012). In particular, the storage of $CO_2$ for EOR is an attractive option as it increases the lifetime of declining oil fields (Liu et al., 2012). The role of CCS-EOR was subject to analysis in many previous studies (McCoy and Rubin, 2009; Rubin et al., 2007; Holloway, 2005). McCoy and Rubin showed that the breakeven price for $CO_2$ increases as the price of crude oil price increases (McCoy and Rubin, 2009). Furthermore, the storage of $CO_2$ in a depleted oil reservoir with EOR credits was reported to reduce the COE of $CO_2$ avoidance by 7–18% (Rubin et al., 2007).

Saudi Arabia is the world's 11th largest emitter of $CO_2$ generating around 494.82 MTon of $CO_2$ in 2014 (CO2 time series 1990–2014 per region/country, 2014). This makes the energy demand Saudi Arabia of a vital interest to the World's economy as Saudi Arabia continues to be the chief oil producing country while oil consumption is rising at an alarming rate (Segar, 2014). Sustainability of the Saudi energy generation sector will be met by three key approaches which are investing in alternative energy, enhancing energy efficiency and fuel economy standards, and integration of CCS (Climate Action Tracker - Saudi Arabia, 2015). Current climate negotiations showed the Kingdom's ambitions to contribute to reducing global $CO_2$ emissions to meet the 2 °C climate target while maintaining its economic growth (Climate Action Tracker - Saudi Arabia, 2015). Furthermore, the recent US shale oil revolution may present a hurdle for investment in alternative sources of energy, as the oil prices remain low. Under such circumstances, investment of CCS in the Kingdom's energy sector can be a strategic option, especially if captured $CO_2$ can be valorised via converting to useful chemicals or utilized for enhanced oil recovery. According the UNFCCC, Saudi Arabia presented its Intended Nationally Determined Contribution (INDC) to the UNFCCC which aims at reducing $CO_2$ emissions by 130 MTon by 2030 (The Intended Nationally Determined Contribution of the Kingdom of Saudi Arabia under the UNFCCC, 2015). This ambitious plan incorporates enhancing energy efficiency measures, increasing use of natural gas and renewable sources of energy, and effective implementation of Carbon Capture and Storage (CCS). To achieve these ambitious climate targets, it is essential to understand the role of energy efficiency and the competition between alternative sources of energy and CCS.

Although there has been some previous research on the power generation and energy systems in Saudi Arabia (Mansouri et al., 2013; Liu et al., 2012; Alkhathlan and Javid, 2013; Almasoud and Gandayh, 2015; Alshehry and Belloumi, 2015; Alyousef and Stevens, 2011; Zuhairy and Sayigh, 1995; Ahmad and Ramana, 2014), none was directed towards analysing low carbon energy transition scenarios. For instance, Mansouri et al. (2013) reported the LCA of electricity sector in Saudi Arabia using only CCS and solar energy which showed enormous opportunity for $CO_2$ reduction. The competition between CCS, renewable and nuclear sources of energy was not analysed. Hence, this study analyses the role of CCS in achieving deep GHG reduction targets in Saudi Arabia while assessing the role of demand management, estimating the $CO_2$ avoidance costs, and investigating the effects of oil prices on the CCS for EOR projects. The relationship between breakeven price of crude oil and CCS and is determined for economic implementation of CCS for EOR projects.

## 2. Methods

### 2.1. Model

The systems analysis was conducted using the MESSAGE software package. MESSAGE is a linear programming optimisation model, developed by the International Institute of Applied Systems Analysis (IIASA), and it was used in many decarbonisation scenarios studies (Schrattenholzer, 1981; Messner and Schrattenholzer, 2000; Klaassen and Riahi, 2007). This model solves the objective function for the least cost under given environmental or cost constraints. MESSAGE can be used to determine the most cost-effective energy mix with optimum allocation of resources, enabling diversification of supplies, reduction of foreign imports, while preserving the environment. MESSAGE requires data on energy demand, environmental constraints, energy conversion efficiency, production costs, and resource capacity. MESSAGE generates the optimum solution to meet the projected energy demand at the lowest cost, while meeting the set environmental or economic targets. The energy system modelled using MESSAGE is shown in Fig. 2.1, which shows the different types of energy resources, conversion technologies, energy carries and end use demand.

The MESSAGE version used in this study has been developed further by the International Atomic Energy Agency (IAEA) to study energy systems for different countries. Based on the data input into MESSAGE, it is possible to study energy systems on a country level, regional or global levels. The data provided for MESSAGE to conduct the optimisation include the production costs of each technology, energy conversion efficiency, $CO_2$ emissions factors, in addition to energy demand and energy resources in Saudi Arabia.

Production costs in this study refer to the investment costs, fixed operating costs, and variable costs for each technology. The projected electricity supply generated by MESSAGE is used to estimate the cumulative production costs for each scenario which is based on the the production costs of a single technology. These are the total costs for electricity supply between 2015 and 2050 under business as usual and mitigation scenarios.

In this formula, the avoidance cost is estimated based on the projected electricity supply costs to meet $CO_2$ reduction targets which is estimated for each avoided ton of $CO_2$. Based on the difference in production costs during the business as usual scenarios, and the $CO_2$ mitigation scenarios, the $CO_2$ avoidance cost is calculated in [\$/kTon] of $CO_2$. Further details about the techno-economic data input into MESSAGE are explained in Sections 2.4–2.6.

### 2.2. Demand scenarios

Demand scenarios for domestic electricity consumption in Saudi Arabia have been developed under two scenarios, as shown in Fig. 2.2. Demand scenario (1) assumes the increase in electricity demand based on historical data without the implementation of energy efficiency measures (Electricity, 2014). Fig. 2.2 shows an increase in energy consumption from 1052 $PJ_e$ in 2015, at a rate of 5.4% every year, to reach 9526 $PJ_e$ by 2050. Implementation of energy efficiency measures such as thermal insulators in Saudi Arabia is expected to reduce the increase in energy demand by 60% (Ghafour, 2014) in 2025, and this is shown in demand scenario (2), Fig. 2.2. Under this scenario, a reduction in the energy demand from 9526 $PJ_e$ to around 3812 $PJ_e$ is achieved in 2050.

### 2.3. $CO_2$ mitigation scenarios

The increase in energy demand is associated with an increase in the $CO_2$ emissions. Table 1 a description of the mitigation scenarios developed in this study.