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## The prospects for coal-to-liquid conversion: A general equilibrium analysis

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## ABSTRACT

We investigate the economics of coal-to-liquid (CTL) conversion, a polygeneration technology that produces liquid fuels, chemicals, and electricity by coal gasification and Fischer–Tropsch process. CTL is more expensive than extant technologies when producing the same bundle of output. In addition, the significant carbon footprint of CTL may raise environmental concerns. However, as petroleum prices rise, this technology becomes more attractive especially in coal-abundant countries such as the U.S. and China. Furthermore, including a carbon capture and storage (CCS) option could greatly reduce its CO<sub>2</sub> emissions at an added cost. To assess the prospects for CTL, we incorporate the engineering data for CTL from the U.S. Department of Energy (DOE) into the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the global economy. Based on DOE's plant design that focuses mainly on liquid fuels production, we find that without climate policy, CTL has the potential to account for up to a third of the global liquid fuels supply by 2050 and at that level would supply about 4.6% of global electricity demand. A tight global climate policy, on the other hand, severely limits the potential role of the CTL even with the CCS option, especially if low-carbon biofuels are available. Under such a policy, world demand for petroleum products is greatly reduced, depletion of conventional petroleum is slowed, and so the price increase in crude oil is less, making CTL much less competitive.

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## 1. Introduction

In this paper, we investigate the economics of a coal-to-liquids (CTL) conversion that can be considered a “polygeneration” technology. There are a variety of polygeneration strategies that have been proposed: in general they use gasification and Fischer–Tropsch (F–T) processes to convert a feedstock (e.g., coal or biomass) to liquid fuels, electricity, and other chemicals. As petroleum prices rise such a technology could help meet demand for transportation fuels.

The CTL technology has been available since the 1920s. In 1944, Germany's CTL plants produced around 90% of its national fuel needs (CTL, 2009; Nexant, Inc., 2008). The technology was then, for the most part, abandoned worldwide because of the availability of cheaper crude oil from the Middle East. The only exception was the development of the CTL industry in South Africa beginning in the 1950s. South Africa's coal-to-liquids industry currently provides around 30% of that nation's transportation fuel (CTL, 2009).

The high oil prices of 2008 and continuing concern about energy security has renewed interest in more expensive energy supply technologies. For instance, the U.S. and China imported around 58% and 45% of the petroleum they consumed in 2007, respectively (EIA, 2009; China Industry Security Guide, 2008). In both countries, proponents of CTL argue that they should take advantage of their abundant coal reserves to reduce their demands on imported energy. It is perhaps the combination of both economic and energy security considerations that has made this coal conversion technology under development in China, South Korea, and Australia (Reuters, 2009).

A problem of CTL conversion, however, is its carbon footprint in the absence of carbon capture and storage (CCS). Studies by EPA (2007) and DOE, 2009 estimate that CTL without CCS could more than double life-cycle greenhouse gas (GHG) emissions compared to those by conventional petroleum-derived fuels. Environmental concerns are reasons that could hinder the development of CTL industry in more developed countries. On the other hand, according to the aforementioned research done by EPA and DOE, with CCS the CTL conversion would yield about the same or possibly somewhat lower life-cycle GHG emissions than petroleum-based fuels. The added cost of CCS would, however, make CTL harder to compete with petroleum-derived fuels than CTL without CCS does. We focus here on a CTL plant design described by DOE (2007) with the following three outputs: diesel,

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naphtha, and electricity. This polygeneration strategy of implementing CTL conversion is similar to Mantripragada and Rubin (2011) and Williams et al. (2009). In addition, we include the additional cost of upgrading naphtha to gasoline, and extend the representation of the CTL technology globally by taking into account the regional differences in input and output prices of this technology. Our goal is to investigate the viability of CTL conversion (without or with CCS) in the face of climate policies to reduce CO<sub>2</sub> emissions. When, where, and under what conditions will this technology become profitable?

Currently, for most research such as DOE (2007, 2009), a common strategy in analyzing the economics of conversion technologies such as CTL is to assume both the crude oil price and the CO<sub>2</sub> price are exogenous. Sensitivity analysis of the results by changing these prices are then provided to see under what circumstances would the technology be viable. While this strategy could provide some preliminary insights, it fails to consider the interactions among different sectors of the global economy, nor does it account for the role of other competing technologies in the global liquid fuels market. To fill this gap, we apply the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium (CGE) model of the global economy as a tool for analysis. We incorporate the engineering data for CTL conversion from DOE (2007) into EPPA, and formulate the CTL technology as a multi-input, multi-output production function where the output shares of the multiple products can be either fixed or responsive to product prices. We find that without climate policy, CTL may become economic especially in coal-abundant countries such as the U.S. and China starting from around 2015, and in this scenario, this technology has the potential to account for about a third of global liquid fuels supply by 2050. However, climate policy proposals, if enforced, would greatly limit its viability even with the CCS option. In such a scenario, CTL may only become viable in countries with less stringent climate policies, or when the low-carbon fuel substitutes are not available.

The paper is organized as follows: Section 2 describes the version of the EPPA model we use, Section 3 presents data on the CTL technology, Section 4 describes the policy simulation scenarios, Section 5 presents the simulation results, and Section 6 provides conclusions.

## 2. The EPPA model

The EPPA model is a multi-region, multi-sector recursive dynamic CGE model of the world economy. The recursive solution approach means that current period investment, savings, and consumption activities are determined by current period prices. Here we adapt and apply a version of EPPA with detail on the refined oil sector, the EPPA-ROIL model. As with the standard EPPA, the global economy is simulated through time to generate scenarios of GHG, aerosols, and other air pollutants emissions from human activities, and it is solved at 5-year intervals from 2000 onward. EPPA is built on the GTAP 5 dataset (Hertel, 1997; Dimaranan and McDougall, 2002), which is supplemented with additional data for the GHG and urban gas emissions and on technologies not separately identified in the basic economic data (Paltsev et al., 2005; Chan et al., 2010).

Similar to the standard EPPA, EPPA-ROIL aggregates the GTAP 5 dataset into the following 16 regions: the United States (USA), Canada (CAN), Mexico (MEX), Japan (JPN), Australia and New Zealand (ANZ), Europe (EUR), Eastern Europe (EET), Russia Plus (FSU), East Asia (ASI), China (CHN), India (IND), Indonesia (IDZ), Africa (AFR), the Middle East (MES), Latin America (LAM), and the Rest of the World (ROW). EPPA-ROIL disaggregates both the downstream and the upstream oil industries of the standard EPPA as shown in Table 1.

This disaggregation allows us to better analyze the source and structure of the liquid fuels supply and the corresponding CO<sub>2</sub> emissions. The details are presented in Choumert et al. (2006). In our analysis, CTL conversion has been incorporated in the model as an additional backstop technology, as shown in Table 1.

In EPPA-ROIL, there are two main components for each region  $r$ : household and producers. (Note that the government is simply modeled as a passive entity that collects taxes and distributes the full value of the proceeds to the household through a lump-sum transfer.) The Household  $i$  owns primary factors  $F_{rf}$  (such as labor, capital, natural resources, and land), provides them to producers, receives income  $M_r$  in the form of factor payments  $R_{rf}$  (wage, capital and resource rents) from producers, and allocates income for consumption  $d_{ri}$  and saving  $s_r$  according to the welfare function  $W_{ri}$ . The utility maximization problem of the household can be expressed as

$$\max_{d_{ri}, s_r} W_{ri}(d_{ri}, s_r) \text{ s.t. } M_r = \sum_f R_{rf} F_{rf} = p_{rs} s_r + p_{ri} d_{ri} \quad (1)$$

where  $W_{ri}$  is represented by a nested Constant Elasticity of Substitution (CES) function, which is constant return to scale (CRTS). By duality and linear homogeneity, the unit expenditure function (the price index for welfare) derived from Eq. (1) can be expressed as

$$p_{rw} = E_r(p_{ri}, p_{rs}) \quad (2)$$

By Shephard's Lemma, the compensated final demand for goods and savings are given by

$$d_{ri} = \bar{m}_r \frac{\partial E_r}{\partial p_{ri}}; \quad s_r = \bar{m}_r \frac{\partial E_r}{\partial p_{rs}} \quad (3)$$

where  $\bar{m}_r$  is the initial level of expenditure in region  $r$ .

Producers (and henceforth production sectors), on the other hand, transform primary factors and intermediate inputs (outputs of other producers) into goods and services, sell them to other domestic or foreign producers, households, or governments, and receive payments from these agents. The producer's problem can be expressed as

$$\max_{y_{ri}, x_{rji}, k_{rji}} \pi_{ri} = p_{ri} y_{ri} - C_{ri}(p_{ri}, R_{rf}, y_{ri}) \text{ s.t. } y_{ri} = \varphi_{ri}(x_{rji}, k_{rji}) \quad (4)$$

where  $\pi$  and  $C$  denote profit and cost functions, respectively, and  $p$  and  $w$  are prices of goods and factors, respectively. Cost functions are also modeled as CES functions. Hence, the producer's optimizing behavior requires the following zero profit condition:

$$p_{ri} = c_{ri}(p_{rj}, R_{rf}) \quad (5)$$

where  $c$  is the unit cost function. Similar to the derivation of (3), in sector  $i$  the intermediate demand for goods  $j$  and the demand for factor  $f$  are

$$x_{rji} = y_{ri} \frac{\partial c_{ri}}{\partial p_{rj}}; \quad k_{rji} = y_{ri} \frac{\partial c_{ri}}{\partial R_{rf}} \quad (6)$$

The system is closed with a set of market clearance equations that determine the equilibrium prices of different goods and factors as shown in (7):

$$y_{ri} = \sum_j x_{rji} + d_{ri}; \quad F_{rf} = \sum_j k_{rji} \quad (7)$$

Note that the property of CRTS also implies an income elasticity of one. To overcome this limit, the elasticity and share parameters are made as functions of income between periods, but not within a period.

The dynamics of EPPA-ROIL are determined by the following: (1) exogenously determined factors such as natural resource assets, growth in population, labor productivity, and land

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