# MIT Joint Program on the Science and Policy of Global Change

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*Y.-H. Henry Chen, John M. Reilly and Sergey Paltsev*

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# The Prospects for Coal-to-Liquid Conversion: A General Equilibrium Analysis

Y.-H. Henry Chen[*†], John M. Reilly[*] and Sergey Paltsev[*]

## 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* $CO_2$ *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.*

## Contents

## 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 (CTLC, 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

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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 (CTLC, 2009).

The high oil prices of 2008 and continuing concern about energy security has renewed interest in more expensive energy supply technologies. 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. According to these same studies, with CCS the conversion would yield about the same or possibly somewhat lower life-cycle GHG emissions than petroleum-based fuels. We focus here on a CTL plant design described by DOE (2007) with the following three outputs: diesel, naphtha, and electricity. We include the additional cost of upgrading naphtha to gasoline. We 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 $CO_2$ 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 $CO_2$ 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 (Paltsev *et al.*, 2009). 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 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 $CO_2$ 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. 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:

$$\max_{\mathrm{d_{ri}},\mathrm{s_r}} W_{ri}(d_{ri}, s_r) \;\; s.t. \;\; M_r = \sum\nolimits_f R_{rf}F_{rf} = p_{rs}s_r + p_{ri}d_{ri} \tag{1}$$

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 Equation (1) can be expressed as:

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

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

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

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:

$$\max_{\mathrm{y_{ri}},\mathrm{x_{rji}},\mathrm{k_{rfi}}} \pi_{ri} = p_{ri}y_{ri} - C_{ri}\left(p_{ri}, R_{rf}, y_{ri}\right) \;\; s.t. \;\; y_{ri} = \varphi_{ri}\left(x_{rji}. k_{rfi}\right) \tag{4}$$

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:

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

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:

$$x_{rji} = y_{ri}\frac{\partial c_{ri}}{\partial p_{rj}}\ ;\ k_{rfi} = y_{ri}\frac{\partial c_{ri}}{\partial R_{rf}} \tag{6}$$

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):

$$y_{ri} = \sum\nolimits_j x_{rji} + d_{ri}\ ;\ F_{rf} = \sum\nolimits_j k_{rfj} \tag{7}$$

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 productivity, and autonomous energy efficiency improvement (AEEI); and 2) endogenously determined factors such as saving and investment. Saving and consumption are aggregated in a Leontief approach that determines the welfare function. All saving is used as investment, which meets the demand for capital goods. The capital is divided into a malleable portion and a vintaged non-malleable portion. In each period a fraction of the malleable capital is frozen to become part of the non-malleable portion. Factor substitution in response to change in relative price is possible for the malleable portion but not the non-malleable one. Interested readers can refer to Paltsev *et al.* (2005) for details. EPPA-ROIL is formulated in a mixed complementary problem (MCP) (Mathiesen 1985; Rutherford 1995) with product exhaustion, market clearance, and income balance conditions using the MPSGE modeling language (Rutherford 1999).

The CTL technology we add is represented by a nested multi-input, multi-output production function, as shown in **Figure 1**. It has a nested constant elasticity of transformation (CET) structure for the output, which includes the liquid fuels bundle (diesel and gasoline) and electricity. For the input, this production function has a nested CES structure, which takes different labor, capital, fuel, carbon permit, and a fixed factor as inputs. The fixed factor represents the limited initial capacity to expand the industry in the early stage of development. We draw the substitution elasticities from a coal integrated combined cycle power plant (coal IGCC) similar to Paltsev *et al.* (2005). While the transformation elasticity between diesel and gasoline is drawn from Choumert *et al.* (2006), the transformation elasticity between liquid fuels bundle and electricity generation is set to zero to represent the plant design of DOE (2007). This design optimizes the production of liquid fuels, using only the off-gas that is unsuitable for liquid fuels production to power the generator.[1]

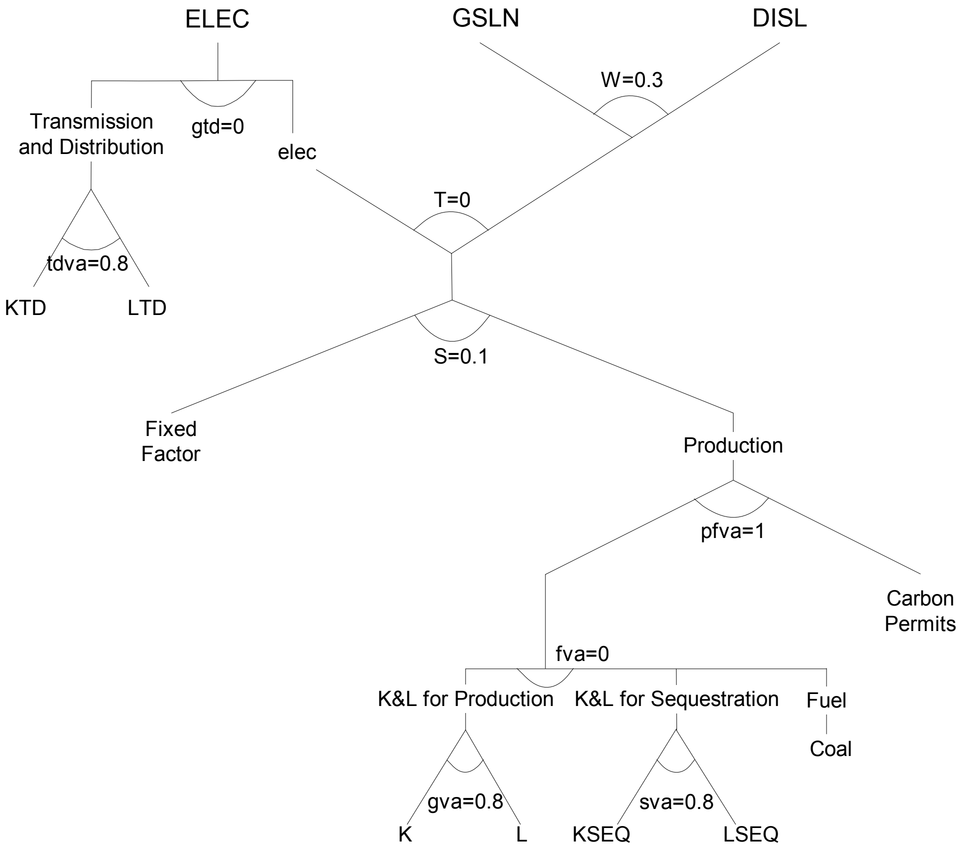

**Figure 1.** CET-CES Representation of the Polygeneration Technology.

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[1] A CTL plant that uses syngas for electricity generation has the flexibility to generate more electricity and less liquid fuels in response to relative price change. This could be modeled by a positive transformation elasticity between liquid fuels bundle and electricity generation.

**Table 1.** Sectors in EPPA4 and EPPA-ROIL (with CTL technology).

| **Sectors in EPPA4** | **Sectors in EPPA-ROIL** |
|---|---|
| **Energy Supply & Conversion** | **Energy Supply & Conversion** |
| *Electricity Generation* | *Electricity Generation* |
| Conventional Fossil | Conventional Fossil |
| Hydro | Hydro |
| Nuclear | Nuclear |
| Wind and Solar | Wind and Solar |
| Biomass | Biomass |
| Advanced Gas | Advanced Gas |
| Advanced Gas with CCS | Advanced Gas with CCS |
| Advanced Coal with CCS | Coal with CCS |
|  | Heavy fuel with CCS |
|  | Coke with CCS |
|  | CTL w/ and w/o CCS |
| *Fuels* | *Fuels* |
| Coal | Coal |
| Crude Oil | Conventional Crude Oil |
|  | Extra-heavy Oil w/ and w/o CCS [a] |
| Refining→a single refined oil product | Refining, Upgrading w/ and w/o CCS [b]→ |
|  | Refinery Gas |
|  | Gasoline |
|  | Diesel |
|  | Heavy Fuel Oil |
|  | Petroleum Coke |
|  | Other Petroleum Products |
|  | CTL w/ and w/o CCS → Diesel and Gasoline |
| Natural Gas | Natural Gas |
| Shale Oil | Shale Oil |
| Gas from Coal | Gas from Coal |
| Liquids from Biomass | Liquids from Biomass |
| ***Other Sectors*** | ***Other Sectors*** |
| Agriculture | Agriculture |
| Energy Intensive Products | Energy Intensive Products |
| Other Industries Products | Other Industries Products |
| Industrial Transportation | Industrial Transportation |
| Services | Services |
| Household | Household |

a. This category includes the oil sands in Canada and the heavy crude oil reserves in Venezuela.
b. Both refining and upgrading yield the six listed refinery products.

## 3. DATA ON CTL CONVERSION AND COSTS

We use the bottom-up engineering data of a CTL plant from the U.S. Department of Energy (DOE, 2007) to benchmark the CTL technology. The CTL plant contains the coal gasification units, Fischer-Tropsch (F-T) reactors, hydrotreating units, hydrocracking units, and electricity generators. In the DOE study, the plant was sized to produce 27819 bbl/day of commercial-grade diesel liquid, 22173 bbl/day of naphtha liquids, which could be upgraded into gasoline, and generate 124.3 MWe of net electricity output. The DOE estimated a by-product for sulfur produced in the process, which we treat as a deduction from the production cost. The plant design includes equipment using 77.1 MWe electricity to separate and compress carbon dioxide, and variable costs and conversion efficiencies assume these operate. However, subsequent off-site use and/or storage of carbon dioxide are not considered in the design. As a result, for CTL without CCS, we deduct the cost of the carbon dioxide separating and compressing unit from the DOE study, and under this consideration, the net electricity output increases to 201.4 MWe. On the other hand, for CTL with CCS, besides including the cost of the carbon dioxide separating and compressing unit, we also include the storage cost ($36 per metric ton of carbon) (Herzog, 2000). In this case, with an approximately 90% carbon dioxide reduction rate, the net electricity output from the CTL plant with CCS decreases to 124.3 MWe. We also include the additional cost of converting naphtha to gasoline (20 cents per gallon) from the DOE study. Finally, after taking into account the regional differences in the prices of inputs and outputs, we are able to extend the representation of CTL technology to all 16 EPPA regions.

### 3.1 Cost, Output, and Mark-up Index

To convert the bottom-up engineering data to top-down representation used in EPPA, we use the following conventions such that 1) labor and fuel costs are from the data of operating and maintenance expenses, and 2) (annualized) capital cost is derived from the total plant costs data. More specifically, we assume: a) a scheme of constant principal repayments in nominal terms as in Osouf (2007), b) a 25-year plant life, which is a standard assumption of EPPA, and c) a 55% vs. 45% debt to equity ratio as in DOE (2007).

For the U.S., the capital, labor, and fuel costs of CTL technology without and with CCS are presented in **Table 2**. In that table, the cost of electricity transmission and distribution (T&D) is from McFarland *et al.* (2008). We use the cost structure of a coal integrated combined cycle power plant with CCS (coal IGCC with CCS), as presented in Paltsev *et al*. (2005), to decompose the T&D and carbon storage costs into their corresponding capital and labor costs.

**Table 3** compares the cost of producing the same bundle of diesel, gasoline, and electricity by CTL conversion with that by conventional technologies. In that table, the unit prices of diesel, gasoline, and electricity are from Choumert *et al.* (2006) and DOE (2000). Table 3 shows that in 2009, CTL without and with CCS cost 13% and 33% more, respectively, than the cost of producing the same output bundle by conventional technologies. The cost mark-ups we specify in the model are those for the 1997 (the base year for EPPA4) data, because the model, when simulated, projects rising oil prices. Because the oil price has risen since 1997, the cost of CTL technology relative to today's oil prices is much more favorable than it was in 1997.

**Table 2.** Cost Structure of CTL Technology in 2009.

| Million US$ (2009 = 100); Capacity Factor = 0.85 | | | | |
|---|---|---|---|---|
| **CTLwithout CCS** | **Capital** | **O&M** | **Fuel** | **Total** |
| **Total Fixed Operating Cost / yr** | | **224** | | |
| Water | | 10 | | |
| Chemicals | | 3 | | |
| Solid Waste Disposal | | 15 | | |
| By-product (Sulfur) | | -5 | | |
| Transmission and Distribution | | 10 | | |
| Other | | 34 | | |
| **Total Variable Operating Cost / yr** | | **65** | | |
| Capital for Transmission and Distribution | 12 | | | |
| Capital for the CTL Plant | 441 | | | |
| **Total Capital Cost / yr** | **454** | | | |
| **Total Fuel Cost / yr** | | | **356** | |
| **Annual Cost** | **454** | **289** | **356** | **1099** |
| **CTL with CCS** (Reduction Rate = 90%) | **Capital** | **O&M** | **Fuel** | **Total** |
| **Total Fixed Operating Cost / yr** | | **224** | | |
| Water | | 10 | | |
| Chemicals | | 3 | | |
| Solid Waste Disposal | | 15 | | |
| By-product (Sulfur) | | -5 | | |
| Transmission and Distribution | | 10 | | |
| Other | | 34 | | |
| Carbon Capture and Storage | | 16 | | |
| **Total Variable Operating Cost / yr** | | **82** | | |
| Capital for Transmission and Distribution | 12 | | | |
| Capital for Carbon Capture and Storage | 104 | | | |
| Capital for the CTL Plant | 441 | | | |
| **Total Capital Cost / yr** | **558** | | | |
| **Total Fuel Cost / yr** | | | **356** | |
| **Annual Cost** | **558** | **306** | **356** | **1219** |

Note: For CTL without CCS, the DOE data included $CO_2$ compressor and associated costs. We have deducted these to represent the cost and performance of CTL without CCS.

**Table 3.** The Output Bundle Cost Comparison for the U.S.

| **CTL w/ CCS (2009 = 100)** | **Diesel** | **Gasoline** | **Electricity** | **Total** |
|---|---|---|---|---|
| Output (TJ/yr) | 53163 | 37801 | 3332 | |
| Unit cost by conventional tech. in 2009 ($/TJ) | 8153 | 10400 | 26817 | |
| Cost of producing a single output by conv. tech. in 2009 (Million $/yr) | 433 | 393 | 89 | 916 |
| Cost of producing the output bundle by CTL w/ CCS (Million $/yr) | | | | 1219 |
| Cost Markup Index | | | | 1.33 |
| Unit cost by conventional tech. in 1997 ($/TJ) | 5962 | 7892 | 23797 | |
| Cost of a single output by conv. tech. in 1997 (Million $/yr) | 317 | 298 | 79 | 695 |
| Cost of producing the output bundle by CTL w/ CCS (Million $/yr) | | | | 1175 |
| Cost Markup Index | | | | 1.69 |

| **CTL w/o CCS (2009 = 100)** | **Diesel** | **Gasoline** | **Electricity** | **Total** |
|---|---|---|---|---|
| Output (TJ/yr) | 53163 | 37801 | 5399 | |
| Unit cost by conventional tech. in 2009 ($/TJ) | 8153 | 10400 | 26817 | |
| Cost of producing a single output by conv. tech. in 2009 (Million $/yr) | 433 | 393 | 145 | 971 |
| Cost of producing the output bundle by CTL w/o CCS (Million $/yr) | | | | 1099 |
| Cost Markup Index | | | | 1.13 |
| Unit cost by conventional tech. in 1997 ($/TJ) | 5962 | 7892 | 23797 | |
| Cost of a single output by conv. tech. in 1997 (Million $/yr) | 317 | 298 | 128 | 744 |
| Cost of producing the output bundle by CTL w/o CCS (Million $/yr) | | | | 1039 |
| Cost Markup Index | | | | 1.40 |

### 3.2 Extending the Representation of CTL Technology to all EPPA Regions

We extend the representation of CTL technology to all EPPA regions by considering the regional differences in input and output prices. For the input prices, the wage rates are from the U.S. Department of Commerce (DOC, 1999), and the interest rates are from the International Monetary Fund (IMF, 2001). We assume 15% and 20% capital return rates for developed countries and developing countries, respectively. Further, each region’s price indices for coal and outputs in the benchmark year are from the GTAP-5 database. We note that simply taking price differences into account, especially the wage rate, might exaggerate differences because lower wage rates in poorer countries may reflect lower productivity. Making up for the lower productivity would require either more domestic labor or hiring employees from developed countries for which the domestic wage rate is not appropriate. To consider this issue, we examine the sensitivity of the results by varying the weight we place on the local wage rate as follows:

Effective wage rate = X · Local wage rate + (1–X) · U.S. wage rate

We assume that X = 0.5 as our benchmark, and perform the sensitivity analysis by considering the extreme cases where X = 1 (the regional wage rate difference can completely reflect the labor cost difference), and X = 0 (the labor cost of each region is the same as that of the U.S.).

For each region, the cost markup index for CTL technology are presented in **Table 4**. Similar to the U.S. story presented in Table 3, we find that in general, each region's EPPA-predicted markup index for 2010 decreases significantly from its benchmark level. This is because while inflation has affected the cost of building and operating a CTL plant the crude oil price has risen faster, thereby increasing the relative costs of the petroleum products with which CTL products must compete. Taking CTL without CCS for example, in 2010, although the EPPA-predicted markup indices for China, India, East Asia, Africa, and Mexico are still greater than one, which means this technology has not become economic yet, they are much lower than those for other regions. This implies that if the crude oil price continues to go up, CTL without CCS may soon become economic in these regions.

**Table 4.** Markup Index for all EPPA Regions.

| | **CTL without CCS** | | **CTL with CCS** | |
|---|---|---|---|---|
| | Markup Index (1997) | Markup Index (2010)* | Markup Index (1997) | Markup Index (2010)* |
| USA | 1.40 | 1.10 | 1.69 | 1.32 |
| CAN | 1.68 | 1.29 | 1.99 | 1.52 |
| MEX | 1.59 | 1.04 | 1.96 | 1.30 |
| JPN | 1.24 | 1.13 | 1.52 | 1.39 |
| ANZ | 1.49 | 1.21 | 1.82 | 1.46 |
| EUR | 1.41 | 1.13 | 1.72 | 1.36 |
| EET | 1.32 | 1.08 | 1.62 | 1.32 |
| FSU | 1.43 | 1.25 | 1.72 | 1.49 |
| ASI | 1.57 | 1.01 | 1.94 | 1.23 |
| CHN | 1.22 | 1.04 | 1.49 | 1.28 |
| IND | 1.37 | 1.03 | 1.74 | 1.30 |
| IDZ | 1.59 | 1.31 | 1.99 | 1.63 |
| AFR | 1.32 | 1.02 | 1.63 | 1.24 |
| MES | 1.94 | 1.39 | 2.39 | 1.69 |
| LAM | 1.66 | 1.15 | 2.05 | 1.40 |
| ROW | 1.53 | 1.12 | 1.90 | 1.38 |

*Predicted markup index by EPPA-ROIL with CTL Technology.

## 4. SCENARIOS

A crucial factor that could affect the prospects for CTL technology is the stance of future carbon policy pledges. During the 2009 Copenhagen Climate Conference, many countries proposed the actions they would take if a binding agreement were achieved. We consider the proposed emissions reduction targets of these countries as one of the climate policy scenarios, as shown in **Table 5**. Although no legally binding agreement was achieved during the conference, taking into account this “Copenhagen scenario” would be an interesting exercise in understanding the impact of a plausible climate policy on global economy. Table 5 also shows how we implement this policy scenario in terms of the 16 EPPA regions.

We develop different scenarios with distinct assumptions on: 1) climate policy, 2) scope of the carbon trade, and 3) the availability of biofuels. The policy scenarios considered include *No Policy*, *Copenhagen Policy*, and *World Policy*.

For the *Copenhagen Policy*, we consider the latest emissions reduction target proposed by each country, as shown in Table 5. While Annex I countries/regions, including ANZ, CAN, EET, EUR, and JPN, are assumed to implement their climate policies in 2010, we assume that the USA and others will not do that until 2015. In particular, we assume that in the case of the USA, the Waxman-Markey bill will be enforced with a medium offset as in Paltsev *et al*. (2009). During the Copenhagen Climate Conference, most countries did not propose targets beyond 2020. For these countries, we assume they will maintain their 2020 targets through 2050 under this scenario.

The scenario *World Policy* could be described as follows. First, the *Copenhagen Policy* scenario will be implemented before 2025. Second, from 2025 onward, the USA will continue its Waxman-Markey scenario with a medium offset, and the other five Annex I countries/regions will continue to cut their $CO_2$ emissions up to 50% below their 1990 levels by 2050. Third, from 2025 onwards, all developing countries agree to cut their $CO_2$ emissions back to their 2000 levels by 2050. In all the scenarios with climate policy, the reductions are linearly interpolated within each time interval.

It is worth noting that during the Copenhagen Meeting, China (CHN) and India (IND) proposed their emissions targets for 2020 based on their carbon emissions intensities of 2005. This means that after 2020, if no further commitments for emissions reduction are proposed, CHN and IND would have growing emissions allowances for as long as their economies continue to grow. They may become major suppliers of emissions allowances if there is an international cap-and-trade. In our analysis, we first consider that allowances are tradable among regions with climate policy, and then for the *Copenhagen Policy* scenario, we also consider the case where there is only regional cap-and-trade, which means the emissions allowances are only allowed to trade within each region rather than among different regions.

**Table 5.** Proposed $CO_2$ Emissions Reduction Goal in the Copenhagen Conference.

| Country | Proposed GHG ($CO_2$-e) Reduction Target for 2020 | Target beyond 2020 | EPPA Region | EPPA Target for the Copenhagen Scenario |
|---|---|---|---|---|
| United States | 17% below 2005 levels by 2020. | 42% below 2005 levels by 2030, and 83% by 2050. | USA | See column 2 & 3, with medium offsets as in Paltsev (2009). |
| Canada | 20% below 2006 levels (equivalent to 3% below 1990 levels) by 2020. | - | CAN | See column 2 & 3. |
| Mexico | 50% below 2000 levels by 2050. | 50% below 2000 levels by 2050. | MEX | See column 2 & 3. |
| Japan | 25% below 1990 levels by 2020. | - | JPN | See column 2 & 3. |
| Australia | 5%(unconditional), 15%(with major developing countries policy) or 25% (with global policy) below 2000 levels by 2020. | - | ANZ | 15% below 2000 levels by 2020. |
| New Zealand | 10% to 20% below 1990 levels by 2020 with global policy and international carbon market. | - | | |
| European Union | 20% (unconditional) or 30% (with other developed and advanced developing countries policy) below 1990 levels | - | EUR | 25% below 1990 levels by 2020. |
| Iceland | 15% below 1990 levels by 2020. | - | | |
| Switzerland | 20% to 30% below 1990 levels by 2020. | - | | |
| Norway | 30% to 40% below 1990 levels by 2020. | - | | |
| Monaco | 20% below 1990 levels by 2020. | - | | |
| Liechtenstein | 20% to 30% below 1990 levels by 2020. | - | | |
| Croatia | 5% below 1990 levels | - | | |
| - | - | - | EET | 20% below 1990 levels by 2020. |
| Russia | 15% to 25% below 1990 levels by 2020. | - | FSU | 15% below 1990 levels by 2020. |
| Ukraine | 20% below 1990 levels by 2020. | - | | |
| Kazakhstan | 15% below 1992 levels by 2020. | - | | |
| Belarus | 5% to 10% below 1990 levels by 2020. | - | | |
| Republic of Korea | 4% below 2005 levels by 2020 or 30% below BAU levels. | - | ASI | 4% below 2005 levels by 2020. |

|  |  |  |  |  |
|---|---|---|---|---|
| Singapore | 16% below BAU levels by 2020. | - |  |  |
| Philippines | 5% below 1990 levels (no information about when this target would be achieved) | - |  |  |
| China | 40% to 45% below its 2005 carbon intensity level by 2020. | - | CHN | 42.5% below its 2005 carbon intensity level by 2020. |
| India | 20% to 25% below its 2005 carbon intensity level by 2020. | - | IND | 22.5% below its 2005 carbon intensity level by 2020. |
| Indonesia | 26% below BAU level by 2020, 41% with international support. | - | IDZ | 26% below BAU level by 2020. |
| South Africa | 34% below BAU levels by 2020 (conditional on provision support). | 42% below BAU by 2025 (conditional on support) | AFR | 34% below BAU levels by 2020. |
| - | - | - | MES | - |
| Brazil | 36.1% to 38.9% below BAU levels by 2020. | - | LAM | 37.5% below BAU levels by 2020. |
| Costa Rica | To become carbon neutral by 2021. | To become carbon neutral by 2021. |  |  |
| Maldives | To become carbon neutral by 2019. | To become carbon neutral by 2019. | ROW | - |
| All Other Developing countries | - | - |  |  |

Data Source: The New York Times (2009); Congressional Budget Office (2009).

For each policy scenario, we consider the cases where biofuels may or may not be available. Biofuels are represented in EPPA-ROIL as an alternative fuel with low carbon emissions. However, as pointed out in Chan *et al.* (2010), a couple of issues can lead one to question the availability of biofuels. One is that cellulosic conversion technology has yet to be demonstrated to be competitive at a large scale. The other is the carbon footprint of producing biofuels from the indirect land use emissions, which is not considered in EPPA-ROIL, could be substantial according to a more recent study (Melillo *et al.*, 2009). The restricted biofuels cases thus represent the possibility that because of technological feasibility and/or carbon footprint implications, biofuels may play a rather limited role in global fuel supplies. The combinations of these different scenarios are presented in **Table 6**.

**Table 6.** Scenarios.

| **Scenario Name** | **No Policy w/ or w/o Bio** | **Copenhagen* w/ or w/o Bio** | **Copenhagen (Only Regional Cap-and-Trade)* w/ or w/o Bio** | **World w/ or w/o Bio** |
|---|---|---|---|---|
| Assumed Annex I Countries' targets for 2010-2050 | | | | |
| Copenhagen targets (including Latest Annex I targets) for 2010-2020 | | ✓ | ✓ | ✓ |
| Assumed Annex I Countries' targets for 2025-2050 | | | | ✓ |
| Assumed Developing Countries' targets for 2025-2050 | | | | ✓ |
| International Cap-and-Trade for Countries with Policy | | ✓ | | ✓ |
| Biofuels available | Yes / No | Yes / No | Yes / No | Yes / No |

* Under this scenario, countries without emissions targets for years after 2020 are assumed to follow their 2020 targets afterward.

## 5. RESULTS

In addition to climate policy, the future of CTL technology is closely related to the global liquid fuels market as well. Thus, besides crude oil and coal based liquid fuels, we also consider several different sources of liquid fuels supply, including oil sands, shale oil, and biofuels which have been presented in EPPA-ROIL.[2] The projections for global liquid fuels supply through 2050 under different scenarios are presented in **Figure 2**. In general, the growing demand for liquid fuels combined with the depletion of crude oil reserves would provide the opportunity for the development of more expensive liquid fuels alternatives, including CTL. More stringent climate policy, on the other hand, would curb the demand for liquid fuels further.

Let us turn to the role of CTL conversion in global liquid fuels supply. Figure 2 shows that under the *No Policy* scenario, CTL has the potential to provide up to a third of the global liquid fuels supply by 2050. In this case, CTL may become economic in regions such as CHN, IND, AFR, and the USA in 2015, as shown in **Figure 3** with the price of crude oil over $91 (in terms of 2010 U.S. dollars), as shown in **Figure 4**. Similarly, for regions like other Annex I and FSU countries, CTL may be feasible during 2020 and 2025, with a crude oil price between $105 and $118 (2010 U.S. dollars). CCS will not enter in this *No Policy* scenario since it increases the cost.

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[2] See Choumert *et al.* (2006).

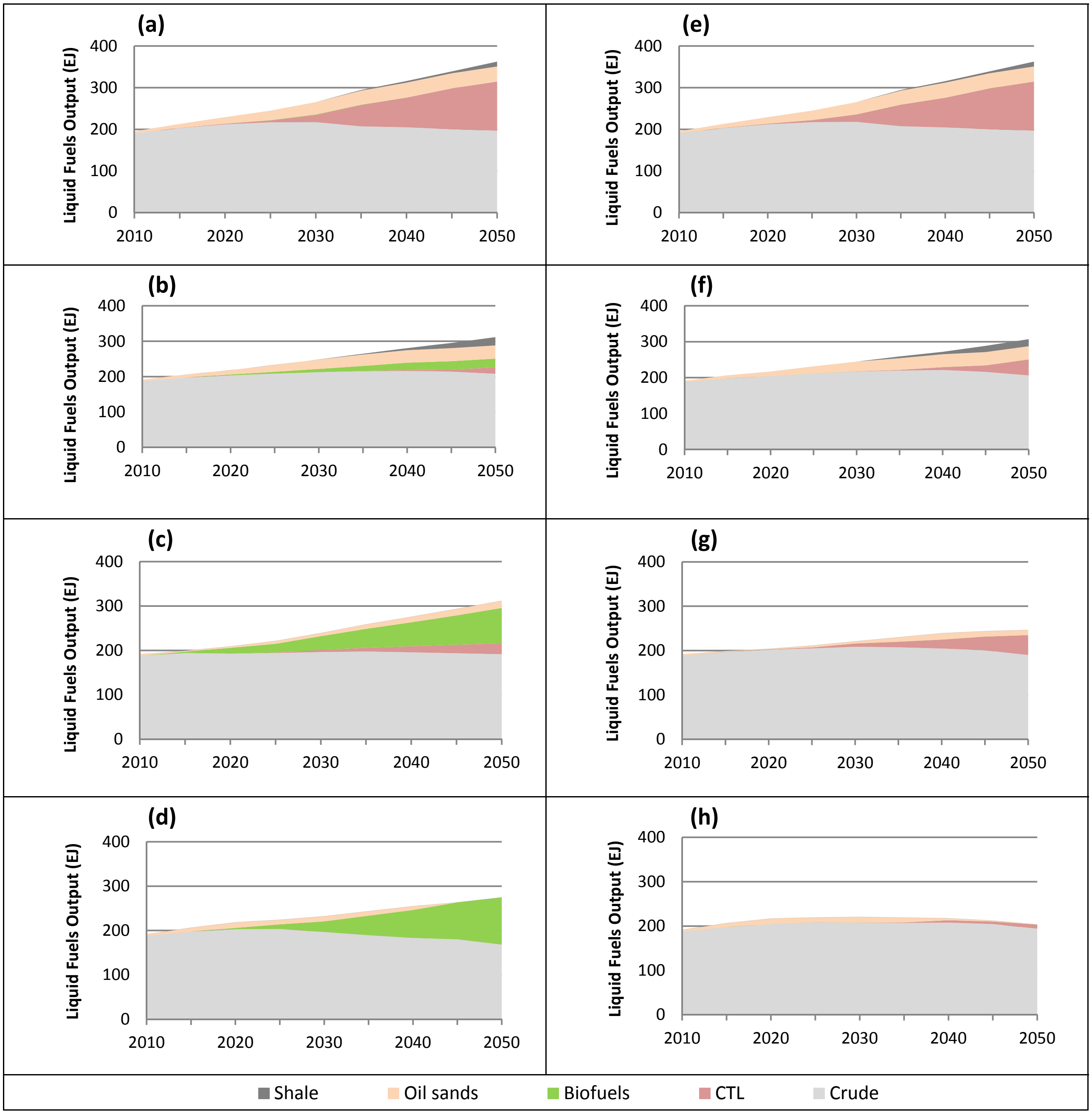

**Figure 2.** World Liquid Fuels Outputs: **(a)** No Policy, **(b)** Policy: Copenhagen, **(c)** Policy: Copenhagen (Only Regional Cap-and-Trade), **(d)** Policy: World, **(e)** No Policy & No biofuels, **(f)** Policy: Copenhagen & No biofuels, **(g)** Policy: Copenhagen (Only Regional Cap-and-Trade) & No biofuels, **(h)** Policy: World & No biofuels.

For the scenario *Copenhagen Policy*, in addition to the availability of biofuels, we also consider whether there is an international cap-and-trade. Figure 3 shows that when biofuels are available, if there is no international cap-and-trade, most liquid fuels output by CTL technology may come from CHN and IND, starting from 2015, without the implementation of CCS. CTL technology in this case may account for about 8% of the world liquid fuels supply by 2050.

However, if there is an international cap-and-trade, most CTL production would move to the USA and AFR, starting from 2025 with CCS, and account for about 5.9% of the world liquid fuels supply.

Note that under the *Copenhagen Policy* scenario, after 2020, the emissions intensity targets of CHN and IND remain unchanged, which means the emissions allowances for these two regions will grow with their GDP levels beyond 2020. As a result, CTL with CCS may still be viable economically in the USA and other Annex I countries, for example, if they can purchase the emissions allowances from CHN or IND, as shown in Figure 3. Figure 3 also shows that when biofuels are not available, CTL with CCS may become economic in regions like the USA, other Annex I countries, and AFR between 2020 and 2030 even if there is no international cap-and-trade. Under this no-biofuels case, CTL technology may account for around 15% to 18% of global liquid fuels supply by 2050, as shown in Figure 2, depending on whether there is an international cap-and-trade.

Under the *World Policy*, the most stringent policy scenario, we find that if biofuels are available, CTL even with CCS may not be economic worldwide. However, if biofuels become unavailable or highly limited, CTL with CCS may enter IND and AFR in 2020 and 2025, respectively, and may enter the USA, other Annex I countries, other developing countries (mainly in Mexico), CHN, and FSU between 2030 and 2040, and account for almost 4% of the world liquid fuels supply by 2050.

We now turn to the role of electricity generation by CTL conversion. Since the plant design of DOE (2007) focuses mainly on liquid fuels production, electricity generation may account for a much smaller part of global electricity supply. **Figure 5** shows that without climate policy, the electricity output by this coal based polygeneration may account for up to 4.6% of global electricity supply; while with climate policy, the electricity output of CTL may contribute less than 2.8% of the global electricity output, depending on the policy scenario and the availability of biofuels.

In short, various climate policy proposals have very different impacts on the allowances of regional $CO_2$ emissions, which in turn have quite distinct implications on the prospects for CTL conversion. The regional $CO_2$ emissions under different climate policy proposals are presented in Appendix A-1, and the $CO_2$ prices under different scenarios are presented in Appendix A-2.

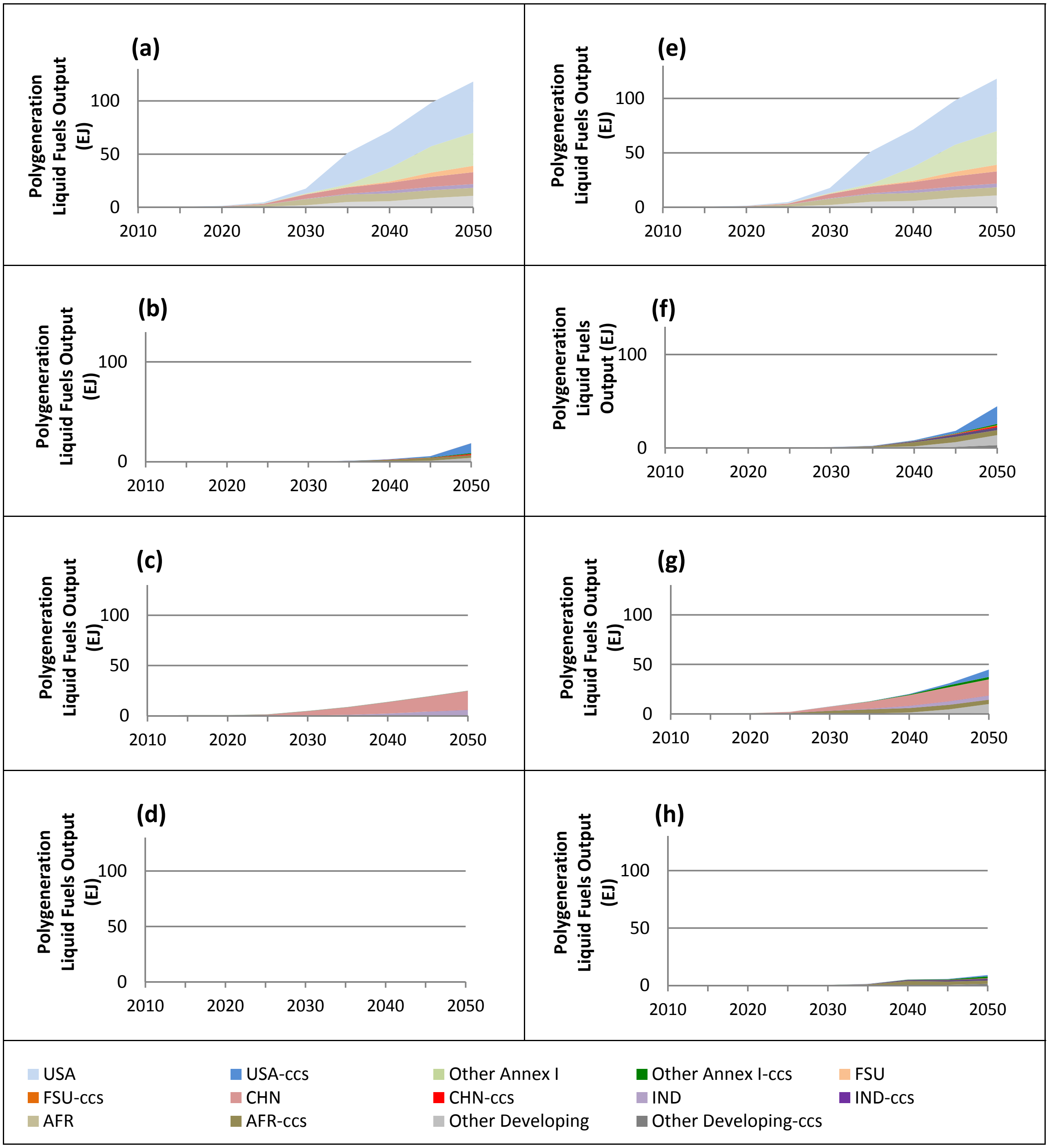

**Figure 3.** CTL Liquid Fuels Outputs: **(a)** No Policy, **(b)** Policy: Copenhagen, **(c)** Policy: Copenhagen, (Only Regional Cap-and-Trade), **(d)** Policy: World, **(e)** No Policy & No biofuels, **(f)** Policy: Copenhagen & No biofuels, **(g)** Policy: Copenhagen (Only Regional Cap-and-Trade) & No biofuels, **(h)** Policy: World & No biofuels.

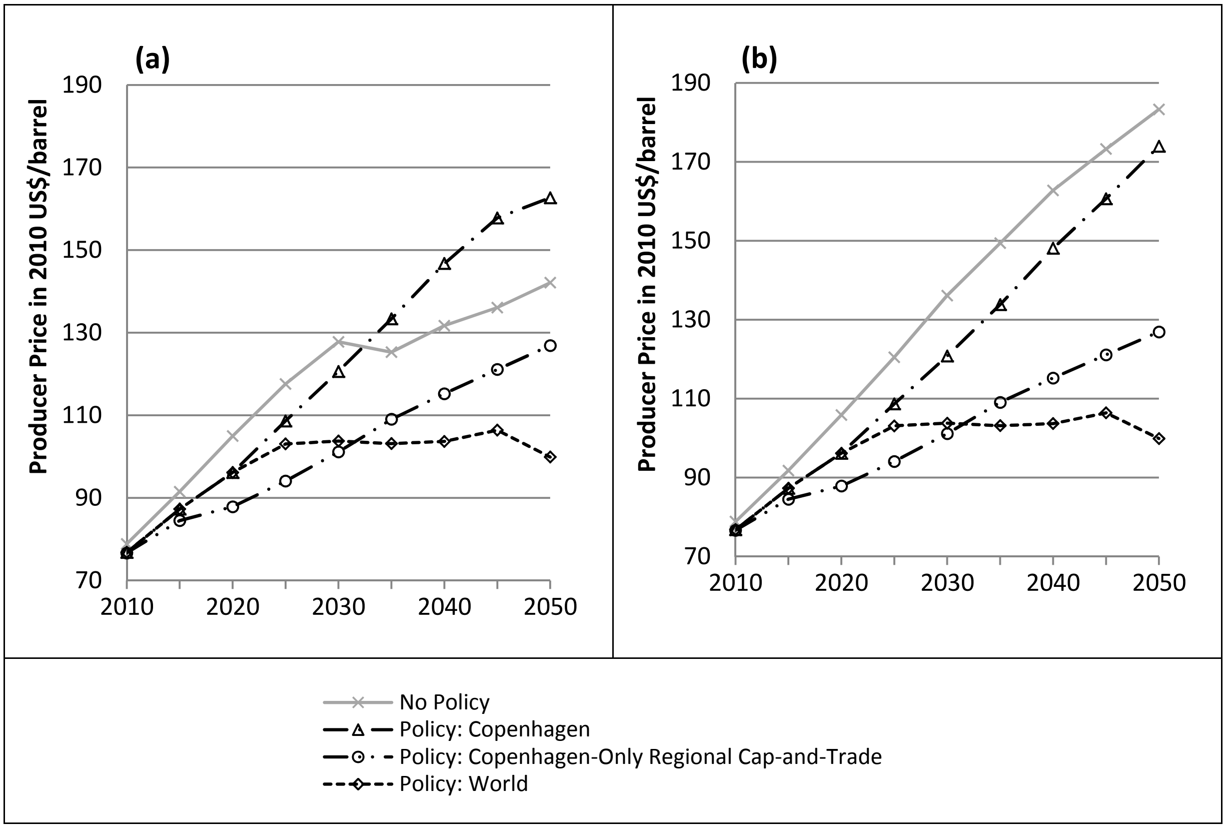

**Figure 4.** Crude Oil Price under Different Scenarios: **(a)** Crude Oil Price: CTL Available, **(b)** Crude Oil Price: CTL Not Available.

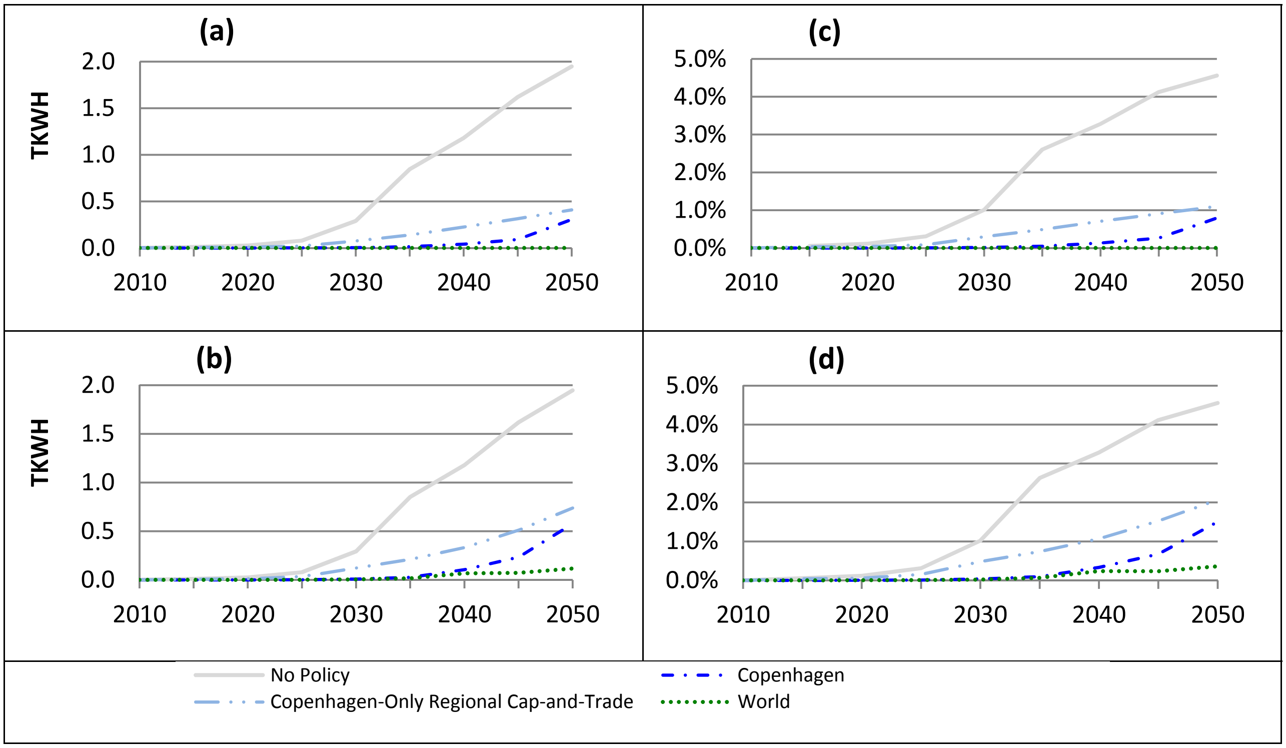

**Figure 5.** Global Electricity Generation by CTL: **(a)** Output: Biofuels Available, **(b)** Output: Biofuels Not Available, **(c)** Share: Biofuels Available, **(d)** Share: Biofuels Not Available.

Finally, we provide a sensitivity analysis on the labor cost of operating a CTL plant. As explained in Section 3.2, the aforementioned labor cost is represented by a weighted average of the local wage rate and the U.S. wage rate. **Table 7** presents the liquid fuels output by CTL under distinct labor cost assumption when biofuels are available. It shows that in general, if the regional wage rate difference does reflect the labor cost difference, more liquid fuels production by CTL technology would be carried out in low wage regions such as CHN and FSU. If, on the other hand, the labor cost of each region is the same as that of the U.S., developing countries no longer enjoy the lower labor costs and more CTL production may shift to developed countries especially the U.S. We also perform the sensitivity analysis for the no biofuels case, and it also shows similar patterns.

**Table 7.** Liquid Fuels Output by CTL.

| | | 2010 | | | 2030 | | | 2050 | |
|---|---|---|---|---|---|---|---|---|---|
| % of local wage | 0% | 50% | 100% | 0% | 50% | 100% | 0% | 50% | 100% |
| Unit: EJ/year | | | | **No Policy** | | | | | |
| USA | 0.00 | 0.00 | 0.00 | 4.90 | 4.50 | 2.18 | 49.05 | 48.04 | 47.69 |
| Other Annex I | 0.00 | 0.00 | 0.01 | 0.71 | 0.76 | 0.79 | 30.22 | 30.93 | 29.76 |
| FSU | 0.00 | 0.00 | 0.00 | 0.07 | 0.21 | 0.26 | 0.28 | 6.03 | 13.67 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CHN | 0.00 | 0.00 | 0.16 | 0.54 | 4.02 | 5.33 | 9.84 | 11.20 | 12.11 |
| IND | 0.00 | 0.00 | 0.04 | 0.23 | 0.29 | 1.18 | 3.67 | 3.57 | 3.40 |
| AFR | 0.00 | 0.00 | 0.31 | 1.01 | 5.71 | 6.01 | 6.92 | 7.45 | 7.46 |
| Other | 0.00 | 0.00 | 0.20 | 0.79 | 2.10 | 5.32 | 11.09 | 10.87 | 11.28 |
| **Policy: Copenhagen** | | | | | | | | | |
| USA | 0.00 | 0.00 | 0.00 | 0.04 | 0.04 | 0.00 | 9.46 | 9.84 | 1.46 |
| Other Annex I | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.26 | 0.76 | 0.83 |
| FSU | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.21 | 1.01 |
| CHN | 0.00 | 0.00 | 0.15 | 0.00 | 0.00 | 0.03 | 0.69 | 0.94 | 5.28 |
| IND | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| AFR | 0.00 | 0.00 | 0.31 | 0.04 | 0.15 | 1.63 | 2.49 | 2.94 | 3.57 |
| Other | 0.00 | 0.00 | 0.20 | 0.01 | 0.03 | 0.08 | 2.02 | 3.77 | 4.05 |
| **Policy: Copenhagen (Only Regional Cap-and-Trade)** | | | | | | | | | |
| USA | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other Annex I | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.03 | 0.03 |
| FSU | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.20 |
| CHN | 0.00 | 0.00 | 0.15 | 1.82 | 4.23 | 5.77 | 16.72 | 18.82 | 19.82 |
| IND | 0.00 | 0.00 | 0.03 | 0.23 | 0.28 | 0.99 | 5.86 | 5.75 | 5.49 |
| AFR | 0.00 | 0.00 | 0.31 | 0.06 | 0.07 | 0.33 | 0.04 | 0.00 | 0.00 |
| Other | 0.00 | 0.00 | 0.20 | 0.01 | 0.01 | 0.09 | 0.17 | 0.18 | 0.12 |
| **Policy: World** | | | | | | | | | |
| USA | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other Annex I | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FSU | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CHN | 0.00 | 0.00 | 0.15 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 |
| IND | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| AFR | 0.00 | 0.00 | 0.31 | 0.00 | 0.00 | 0.29 | 0.00 | 0.00 | 0.00 |
| Other | 0.00 | 0.00 | 0.20 | 0.00 | 0.01 | 0.07 | 0.00 | 0.00 | 0.00 |

50% scenario: wage in CTL sector = $50\% \cdot local\ wage + 50\% \cdot US\ wage$
0% scenario: wage in CTL sector = $0\% \cdot local\ wage + 100\% \cdot US\ wage$
100% scenario: wage in CTL sector = $100\% \cdot local\ wage + 0\% \cdot US\ wage$

## 6. CONCLUSIONS

Due to the significant rise of crude oil prices in recent years, analyzing the prospects for alternative conversion technologies such as CTL has been of great interest. Unlike current research which often relies on sensitivity analysis of the results by changing the price that is exogenous to the analysis, we assess the commercial viability of CTL under the EPPA model, a CGE model of the global economy. Under this framework, we are able to investigate how could different climate policy proposals and the availability of other fuel alternatives influence the future of CTL conversion, and what could be the role of CTL on global liquid fuels supply. We find that without climate policy, CTL has the potential to account for around a third of global liquid fuels by 2050. The viability of CTL, however, becomes quite limited in regions with climate policy due to the high conversion cost and huge carbon footprint. Although adding CCS could reduce $CO_2$ emissions, the additional cost from implementing CCS, makes CTL less attractive.

The main contribution of our research is to provide a comprehensive and consistent approach to investigate the future of CTL conversion, a strategy which has been discussed intensively especially in coal-abundant countries. In addition, the multi-input and multi-output structure we develop to represent CTL conversion could also be applied to other polygeneration approaches that produce different fixed or variable output shares or that relied on other feedstocks. Thus, future research may explore coal-biomass-to-liquid (CBTL) or biomass-to-liquid (BTL) processes which, while probably having higher conversion costs, could have significant benefit in terms of reduced $CO_2$ emissions.

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## APPENDIX

### Regional $CO_2$ Emissions Under Different Climate Policy Proposals

**Figure A1** presents the global $CO_2$ emissions under different scenarios. We find that if the Copenhagen target of each country could be seriously enforced, it may reduce about half of the developing countries' emissions relative to *No Policy* scenario by 2050. Since under the *Copenhagen Policy* scenario, CHN and IND may have growing emissions allowances after 2020, if there is an international cap-and-trade, they may provide a huge amount of $CO_2$ allowances to other developed countries and thus curb the $CO_2$ price, as shown in **Figure A2.** If, however, there is no international cap-and-trade, then the USA and other Annex I countries have to cut their emissions further. This shifts the emissions from the developed world to the developing countries, as shown in Figure A1.

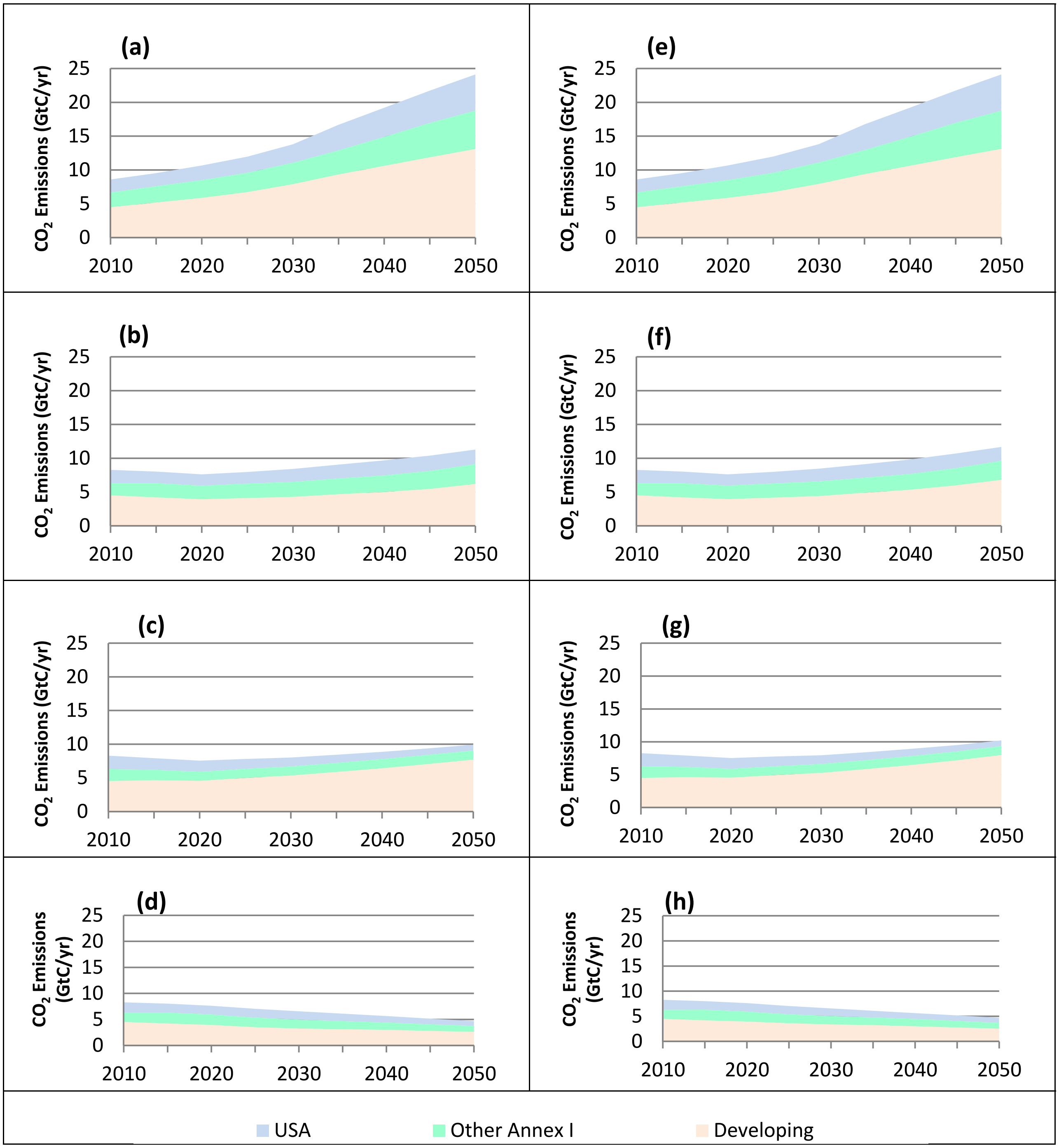

**Figure A1.** Global CO$_2$ emissions under different scenarios: **(a)** No Policy, **(b)** Policy: Copenhagen, **(c)** Policy: Copenhagen (Only Regional Cap-and-Trade), **(d)** Policy: World, **(e)** No Policy & No biofuels, **(f)** Policy: Copenhagen & No biofuels, **(g)** Policy: Copenhagen (Only Regional Cap-and-Trade) & No biofuels, **(h)** Policy: World & No biofuels.

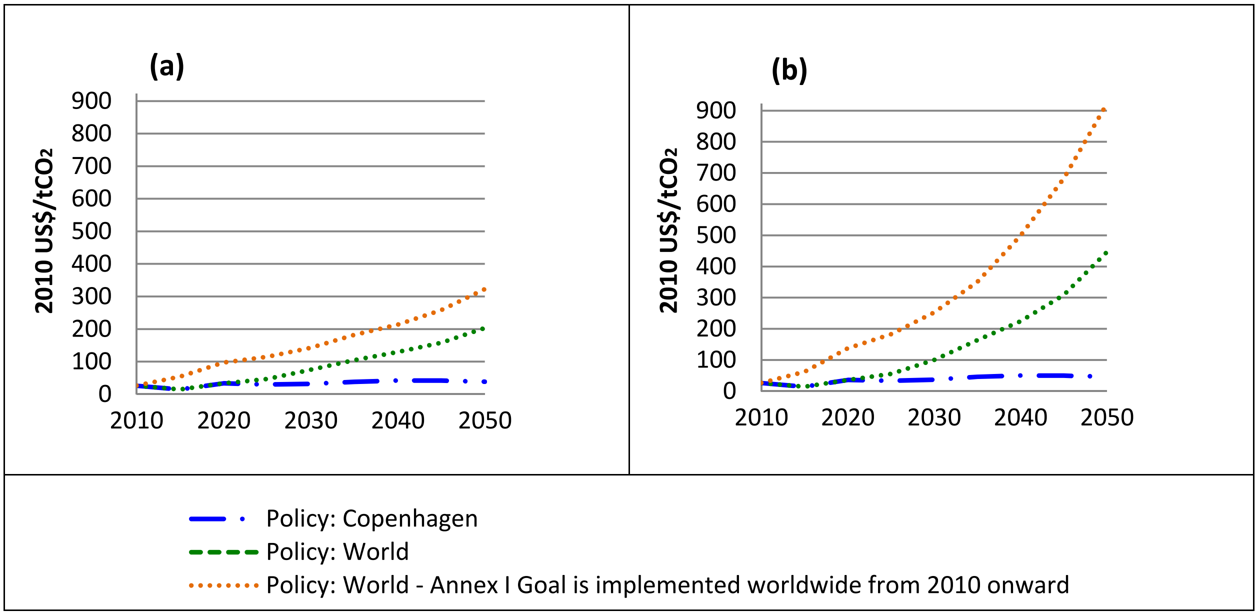

**Figure A2.** $CO_2$ Price under Different Scenarios: **(a)** Biofuels Available, **(b)** Biofuels Not Available.

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