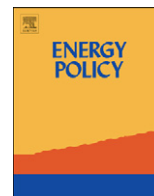




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The prospects for coal-to-liquid conversion: A general equilibrium analysis

Y.-H. Henry Chen^{a,*}, John M. Reilly^b, Sergey Paltsev^b^a Development Research Group at the World Bank, 1818 H Street NW, Washington, DC 20433, USA^b MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA 02139, USA

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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 CO₂ 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,

* Corresponding author.

E-mail addresses: chenyh@colorado.edu (Y.-H. Henry Chen), reilly@mit.edu (J.M. Reilly), paltsev@mit.edu (S. Paltsev).

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 CO₂ 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 CO₂ 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 CO₂ 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

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

where π 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

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

Sectors in EPPA4	Sectors in EPPA-ROIL
Energy supply and conversion	Energy supply and conversion
<i>Electricity generation</i>	<i>Electricity generation</i>
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
<i>Fuels</i>	<i>Fuels</i>
Coal	Coal
Crude oil	Conventional crude oil
	Extra-heavy oil w/and w/o CCS ^a
	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
	Shale oil
	Gas from coal
	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.

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 profit 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 Fig. 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

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 27 819 bbl/day of commercial-grade diesel liquid, 22 173 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 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

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.

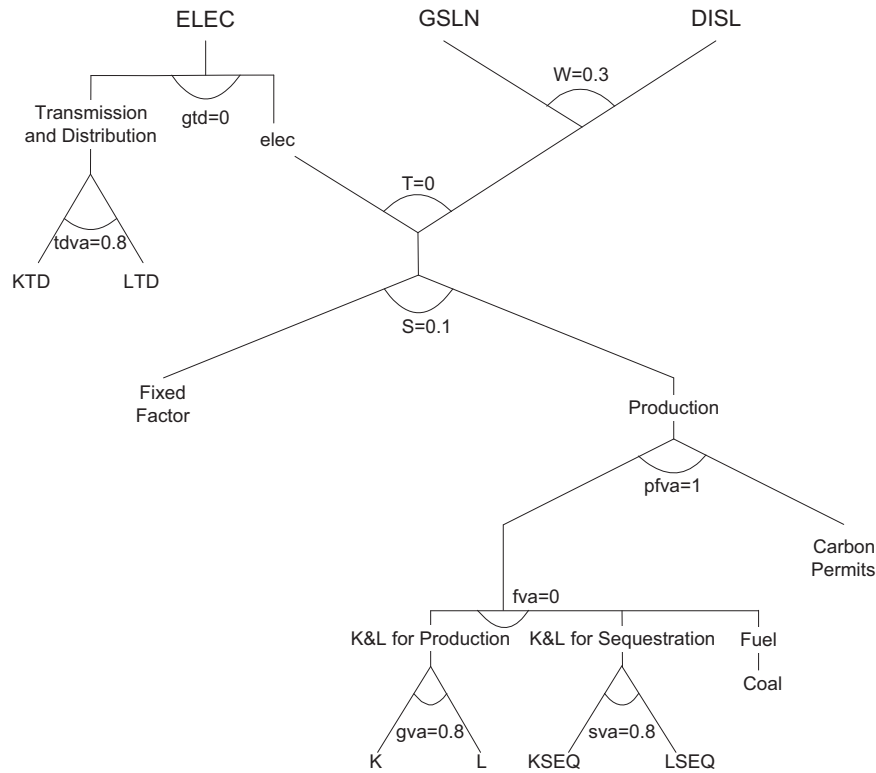


Fig. 1. CET-CES representation of the polygeneration CTL technology.

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 or 9.82 per metric ton of CO_2) (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.

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:

$$\text{Effective wage rate} = X \text{ Local wage rate} + (1-X) \text{U.S. wage rate}$$

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 2

Cost structure of CTL technology in 2009.

Million US\$ (2009=100); capacity factor=0.85				
	Capital	O&M	Fuel	Total
<i>CTL without CCS</i>				
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
<i>CTL with CCS (reduction rate=90%)</i>				
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 CO₂ 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.

	Diesel	Gasoline	Electricity	Total
<i>CTL w/CCS (2009=100)</i>				
Output (TJ/yr)	53 163	37 801	3332	
Unit cost by conventional tech. in 2009 (\$/TJ)	8153	10 400	26 817	
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	23 797	
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
<i>CTL w/o CCS (2009=100)</i>				
Output (TJ/yr)	53 163	37 801	5399	
Unit cost by conventional tech. in 2009 (\$/TJ)	8153	10 400	26 817	
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	23 797	
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

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

Table 4

Markup index for all EPPA regions.

	CTL without CCS		CTL with CCS	
	Markup index (1997)	Markup index (2010) ^a	Markup index (1997)	Markup index (2010) ^a
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

^a Predicted markup index by EPPA-ROIL with CTL technology.

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,

Table 5
Proposed CO₂ emissions reduction goal in the Copenhagen conference.

Country	Proposed GHG (CO ₂ -e) reduction		EPPA region	EPPA target for the Copenhagen scenario
	Target for 2020	Target beyond 2020		
United States	17% below 2005 levels by 2020	42% below 2005 levels by 2030, and 83% by 2050	USA	See columns 2 and 3, with medium offsets as in Paltsev et al. (2009)
Canada	20% below 2006 levels (equivalent to 3% below 1990 levels) by 2020	–	CAN	See columns 2 and 3
Mexico	50% below 2000 levels by 2050	50% below 2000 levels by 2050	MEX	See column 2 and 3
Japan	25% below 1990 levels by 2020	–	JPN	See columns 2 and 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	10–20% 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	20–30% below 1990 levels by 2020	–		
Norway	30–40% below 1990 levels by 2020	–		
Monaco	20% below 1990 levels by 2020	–		
Liechtenstein	20–30% below 1990 levels by 2020	–		
Croatia	5% below 1990 levels	–		
–	–	–	EET	20% below 1990 levels by 2020
Russia	15–25% 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	5–10% 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	40–45% below its 2005 carbon intensity level by 2020	–	CHN	42.5% below its 2005 carbon intensity level by 2020
India	20–25% 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	36.1–38.9% 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).

Table 6
Scenarios.

Scenario name	No Policy w/or w/o Bio	Copenhagen ^a w/or w/o Bio	Copenhagen (only regional cap-and-trade) ^a 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

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

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 CO₂

emissions up to 50% below their 1990 levels by 2050. Third, from 2025 onwards, all developing countries agree to cut their CO₂ 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

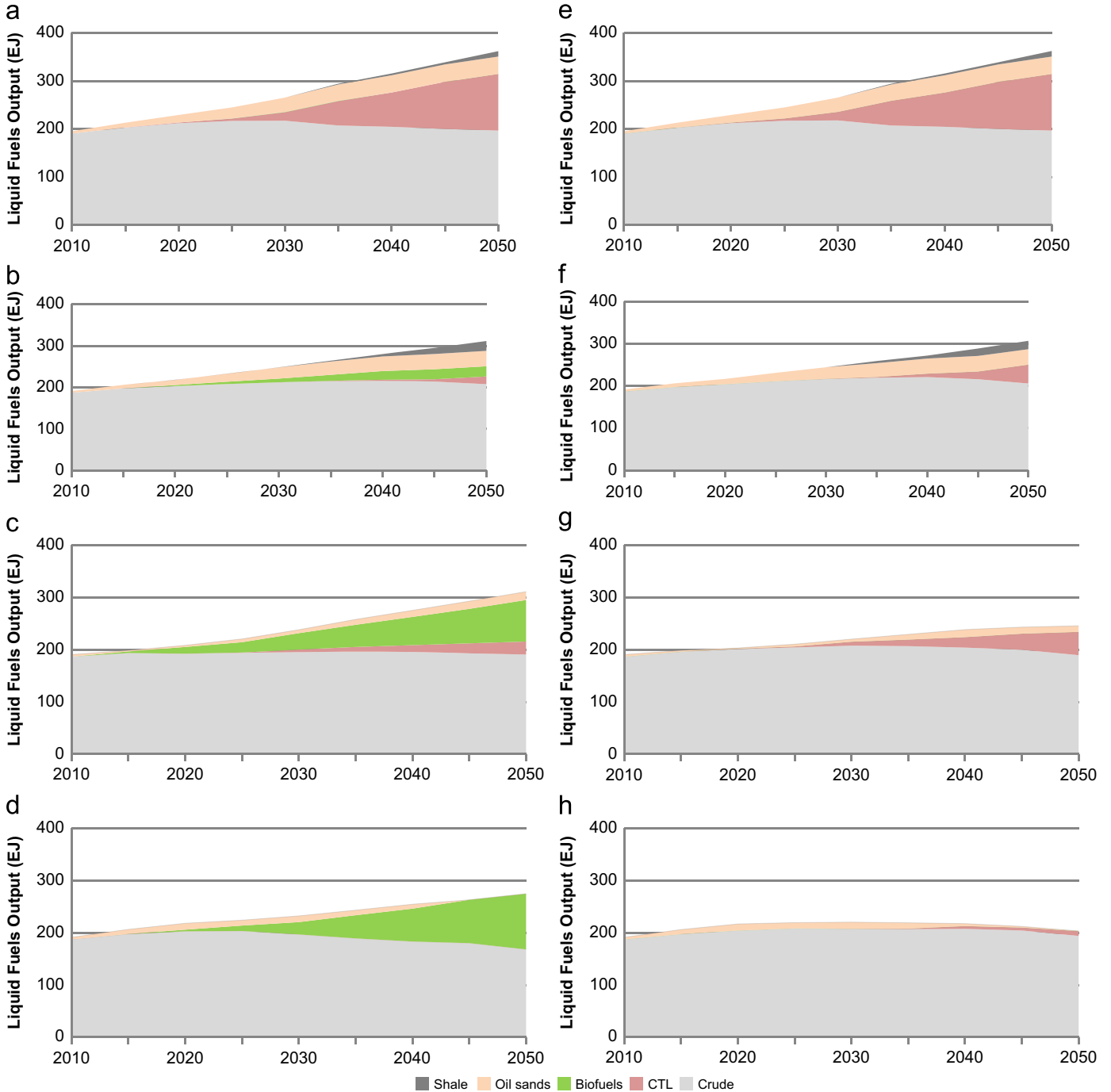


Fig. 2. World liquid fuels outputs: (a) No Policy, (b) Policy: Copenhagen, (c) Policy: Copenhagen (only regional cap-and-trade), (d) Policy: World, (e) No Policy and no biofuels, (f) policy: Copenhagen and no biofuels, (g) Policy: Copenhagen (Only regional cap-and-trade) & no biofuels, (h) Policy: World and no biofuels.

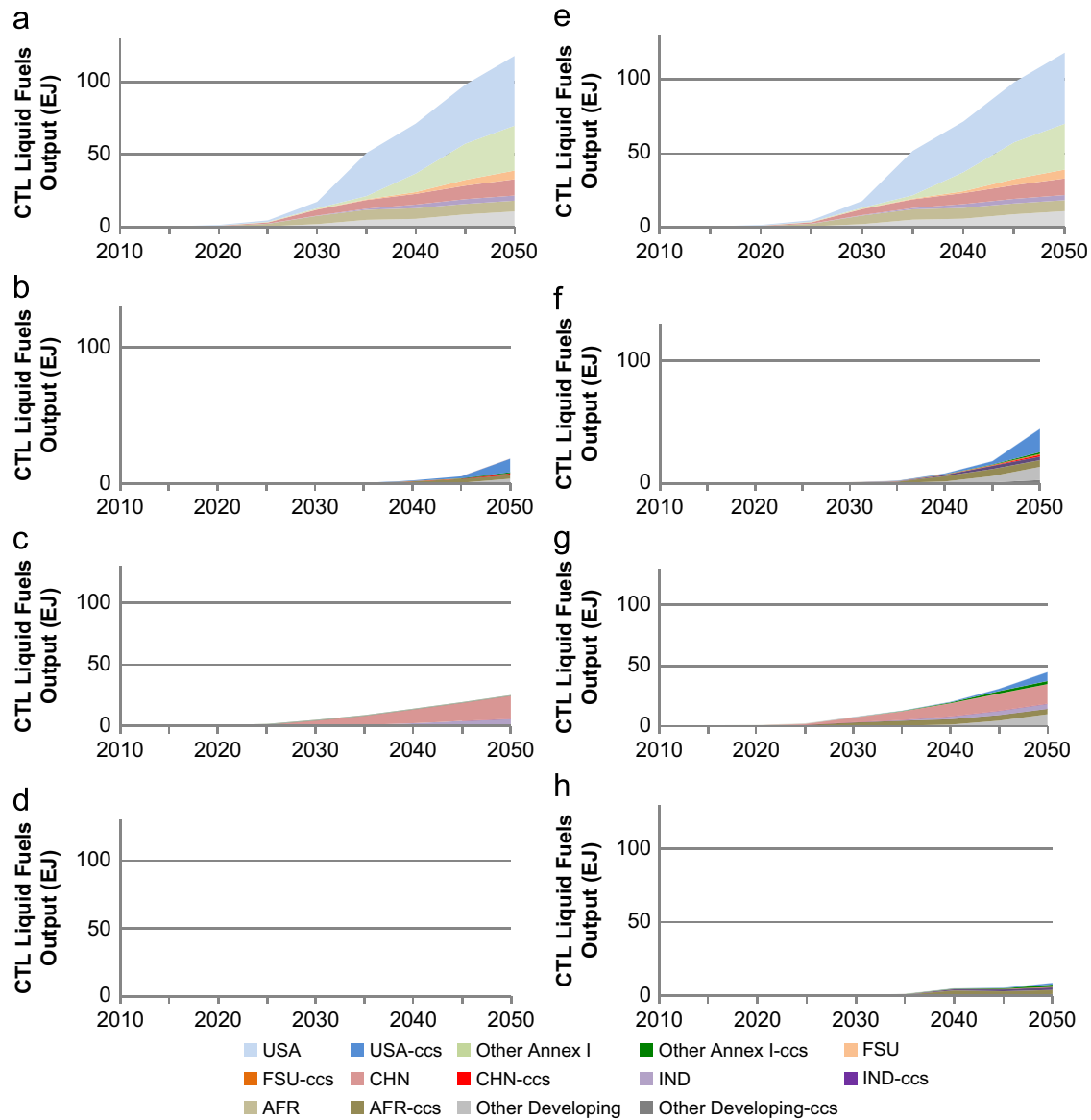


Fig. 3. CTL liquid fuels outputs: (a) No Policy, (b) Policy: Copenhagen, (c) Policy: Copenhagen (only regional cap-and-trade), (d) Policy: World, (e) No Policy and no biofuels, (f) Policy: Copenhagen and no biofuels, (g) Policy: Copenhagen (only regional cap-and-trade) and no biofuels, (h) Policy: World and no biofuels.

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.

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.

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 In this section, we first explore the potential roles of CTL in global liquid fuels supply and electricity generation, and then provide sensitivity analyses on different labor cost and long-term crude oil price assumptions.

5.1. The roles of CTL in global energy supply

The projections for global liquid fuels supply through 2050 under different scenarios are presented in Fig. 2. In general, the growing demand for liquid fuels combined with the depletion of

² See Choumert et al. (2006).

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. Fig. 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 Fig. 3 with the price of crude oil over \$91 (in terms of 2010 U.S. dollars), as shown in Fig. 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.

For the scenario *Copenhagen Policy*, in addition to the availability of biofuels, we also consider whether there is an international cap-and-trade. Fig. 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 Fig. 3. Fig. 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 15–18% of global liquid fuels supply by 2050, as shown in Fig. 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,

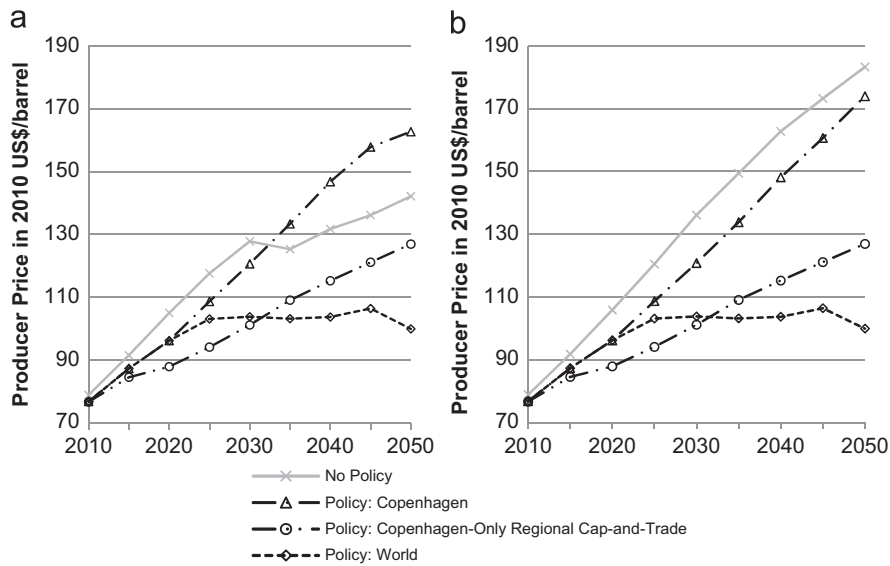


Fig. 4. Crude oil price under different scenarios: (a) crude oil price: CTL available, (b) crude oil price: CTL not available.

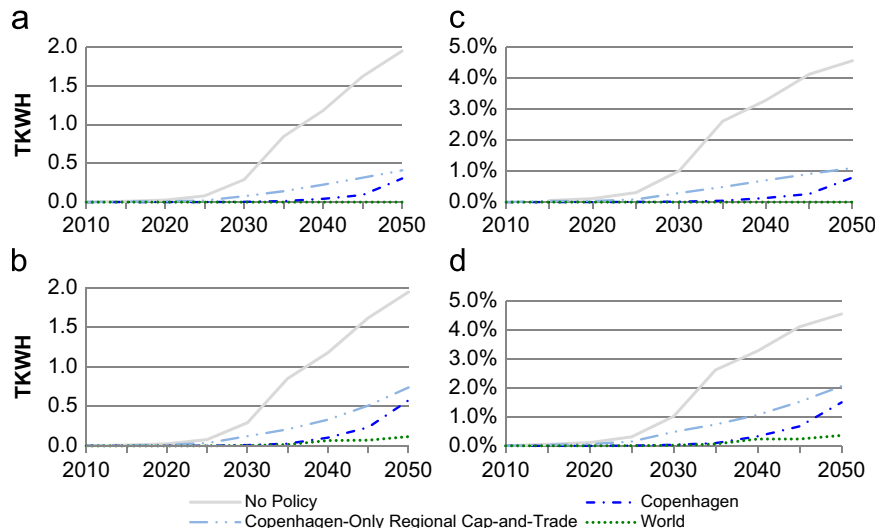


Fig. 5. Global electricity generation by CTL: (a) output: biofuels available, (b) output: biofuels not available, (c) share: biofuels available, (d) share: biofuels not available.

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. Fig. 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 CO₂ emissions, which in turn have quite distinct implications on the adoption of CTL conversion, producer price of crude oil, and GDP levels, as presented in Appendix A1. The regional CO₂ emissions and CO₂ prices under different climate policy proposals are presented in Appendix A2.

5.2. Sensitivity analyses

Let us begin from 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

Table 7
CTL liquid fuels output under different labor cost assumption.

% of local wage	2010			2030			2050		
	0%	50%	100%	0%	50%	100%	0%	50%	100%
Unit: EJ/yr	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 (international cap-and-trade)								
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 (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 (international 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	0.00	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% · local wage + 50% · US wage.
0% scenario: wage in CTL sector = 0% · local wage + 100% · US wage.
100% scenario: wage in CTL sector = 100% · local wage + 0% · US wage.

Table 8
CTL liquid fuels output under different long-term crude oil price scenarios.

	2010 base	+25%	2030 base	+25%	2050 base	+25%
	No Policy					
USA	0.00	0.30	4.50	27.74	48.04	56.64
Annex I	0.00	0.22	0.76	17.15	30.93	42.85
FSU	0.00	0.00	0.21	0.62	6.03	8.72
CHN	0.00	0.18	4.02	5.09	11.20	12.09
IND	0.00	0.04	0.29	1.52	3.57	3.57
AFR	0.00	0.30	5.71	4.82	7.45	7.82
Other	0.00	0.39	2.10	5.97	10.87	13.49
	Policy: Copenhagen (international cap-and-trade)					
USA	0.00	0.29	0.04	11.78	9.84	27.67
Annex I	0.00	0.00	0.00	0.47	0.76	14.71
FSU	0.00	0.00	0.00	0.00	0.21	0.22
CHN	0.00	0.16	0.00	0.98	0.94	5.78
IND	0.00	0.04	0.00	0.74	0.00	0.22
AFR	0.00	0.31	0.15	2.55	2.94	4.47
Other	0.00	0.41	0.03	1.98	3.77	8.79
	Policy: Copenhagen (regional cap-and-trade)					
USA	0.00	0.29	0.00	7.02	0.00	2.32
Annex I	0.00	0.01	0.00	0.03	0.03	1.69
FSU	0.00	0.00	0.00	0.19	0.02	5.40
CHN	0.00	0.16	4.23	6.85	18.82	19.99
IND	0.00	0.04	0.28	1.50	5.75	6.19
AFR	0.00	0.31	0.07	2.27	0.00	0.61
Other	0.00	0.41	0.01	1.29	0.00	10.03
	Policy: World (international cap-and-trade)					
USA	0.00	0.29	0.00	8.14	0.00	0.79
Annex I	0.00	0.00	0.00	0.07	0.00	0.00
FSU	0.00	0.00	0.00	0.00	0.00	0.00
CHN	0.00	0.16	0.00	0.45	0.00	0.52
IND	0.00	0.04	0.00	0.10	0.00	0.00
AFR	0.00	0.31	0.00	2.50	0.00	0.00
Other	0.00	0.41	0.01	0.69	0.00	0.03

Base scenario: crude oil price is \$79 per barrel.

+25% scenario: Crude oil price is 25% higher than the base scenario.

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.

We also provide a sensitivity analysis based on a different long-term crude oil price assumption. Note that while the *price index* of crude oil is determined endogenously by our model, it could be mapped onto a higher crude oil price, which suggests the cost markup of CTL technology would drop and this technology will become more attractive. When this research was conducted in early 2010, the cost markup index for CTL was calculated based on the crude oil price at that time, which was around \$79 per barrel. We assume this price to be the long-term (equilibrium) crude oil price since explaining the short term fluctuation of crude oil price is beyond the scope of our model, and the long-term crude oil price should be more relevant in assessing the economics of CTL. Here, we consider another long-term crude oil price scenario with a 25% higher crude oil price (around \$100 per barrel in 2010).³ The results presented in Table 8 show that with a higher crude oil price, although CTL would become economic earlier with a higher level of outputs,

³ Note that as mentioned in Section 2, EPPA is solved at five-year intervals from 2000 onward.

the basic story for its future prospects is similar. More specific, although CTL may be economically feasible for some regions in the next 20 years, under the most stringent climate policy scenario, it is barely economic in 2050.

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 CO₂ 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 CO₂ emissions.

Acknowledgments

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Table A1
CTL liquid fuels output, crude oil producer prices, and change in GDP.

	2010	2030	2050	2010	2030	2050	2010	2030	2050
No Policy									
	Liquid fuels from CTL (EJ/yr)			Crude oil producer price 2010=100			% Change in GDP from No Policy		
World	0	17.59	118.09	78.86	127.79	142.12	0%	0%	0%
USA	0	4.5	48.04				0%	0%	0%
Other Annex I	0	0.76	30.93				0%	0%	0%
FSU	0	0.21	6.03				0%	0%	0%
CHN	0	4.02	11.2				0%	0%	0%
IND	0	0.29	3.57				0%	0%	0%
AFR	0	5.71	7.45				0%	0%	0%
Other	0	2.1	10.87				0%	0%	0%
Policy: Copenhagen (international cap-and-trade)									
	Liquid fuels from CTL (EJ/yr)			Crude oil producer price 2010=100			% Change in GDP from No Policy		
World	0	0.22	18.46	76.79	120.61	162.68	-0.23%	-0.90%	-2.22%
USA	0	0.04	9.84				0.01%	-0.53%	-2.10%
Other Annex I	0	0	0.76				-0.54%	-1.21%	-2.82%
FSU	0	0	0.21				-0.01%	-0.26%	-1.37%
CHN	0	0	0.94				0.04%	-0.21%	-0.16%
IND	0	0	0				0.07%	-0.15%	-0.41%
AFR	0	0.15	2.94				0.01%	-2.31%	-2.85%
Other	0	0.03	3.77				0.00%	-0.90%	-1.78%
Policy: Copenhagen (regional cap-and-trade)									
	Liquid fuels from CTL (EJ/yr)			Crude oil producer price 2010=100			% Change in GDP from No Policy		
World	0	4.59	24.8	76.65	101.13	126.89	-0.27%	-2.00%	-4.12%
USA	0	0	0				0.02%	-0.50%	-2.86%
Other Annex I	0	0	0.03				-0.63%	-2.70%	-4.51%
FSU	0	0	0.02				-0.02%	-0.91%	-3.75%
CHN	0	4.23	18.82				0.03%	-2.49%	-2.46%
IND	0	0.28	5.75				0.07%	-0.36%	-0.49%
AFR	0	0.07	0				0.01%	-3.76%	-6.84%
Other	0	0.01	0.18				-0.01%	-2.89%	-6.12%
Policy: World (international cap-and-trade)									
	Liquid fuels from CTL (EJ/yr)			Crude oil producer price 2010=100			% Change in GDP from No Policy		
World	0	0	0	76.79	103.78	99.90	-0.23%	-1.63%	-4.74%
USA	0	0.01	0				0.01%	-0.66%	-2.70%
Other Annex I	0	0	0				-0.54%	-1.93%	-5.06%
FSU	0	0	0				-0.01%	-0.86%	-5.66%
CHN	0	0	0				0.04%	-0.26%	-1.99%
IND	0	0	0				0.07%	-1.85%	-5.39%
AFR	0	0	0				0.01%	-4.03%	-8.21%
Other	0	0.01	0				0.00%	-2.83%	-8.08%

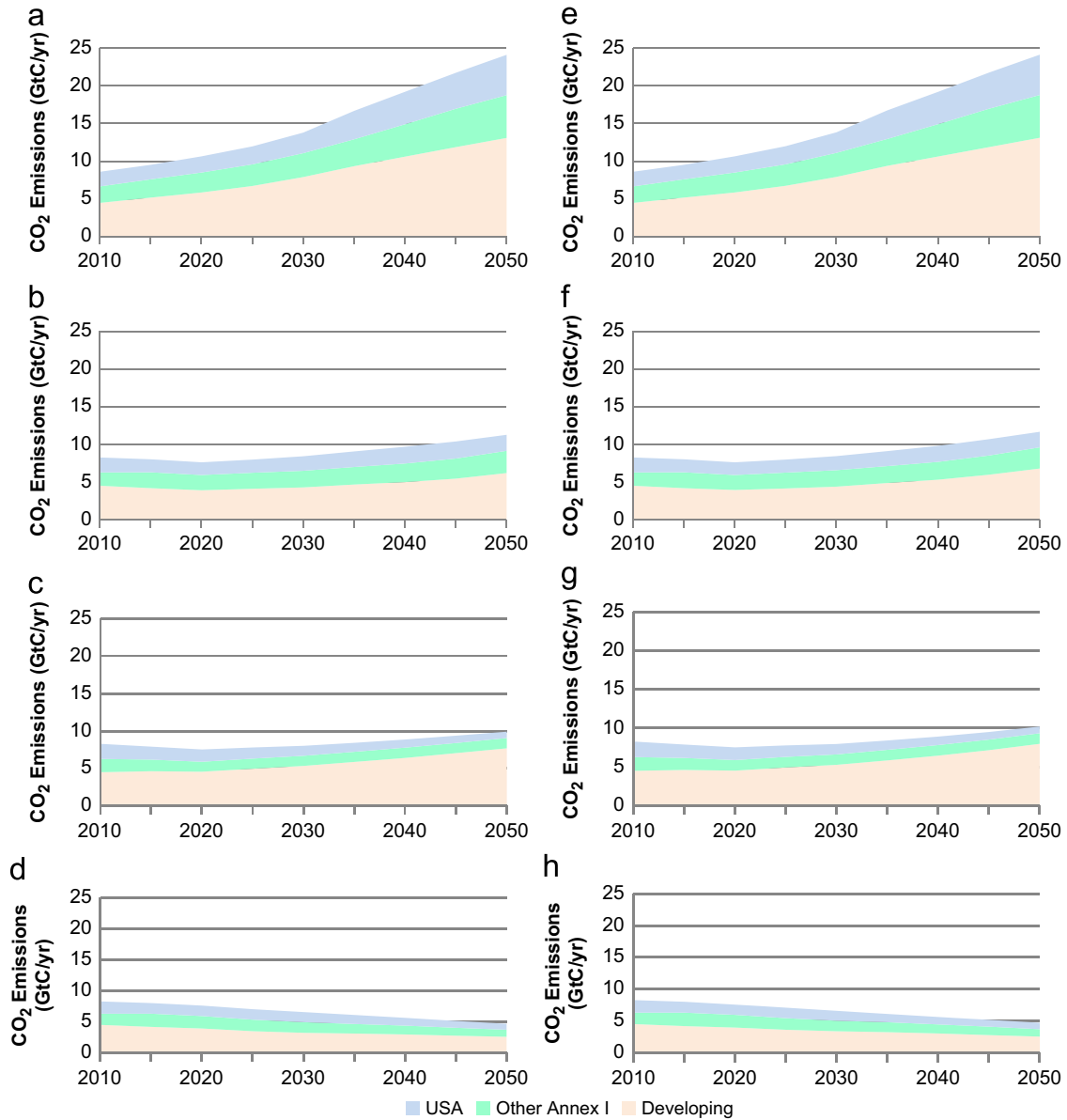


Fig. A1. Global CO₂ emissions under different scenarios: (a) No Policy, (b) Policy: Copenhagen, (c) Policy: Copenhagen (only regional cap-and-trade), (d) Policy: World, (e) No Policy and no biofuels, (f) Policy: Copenhagen and no biofuels, (g) Policy: Copenhagen (only regional cap-and-trade) and no biofuels, (h) Policy: World and no biofuels.

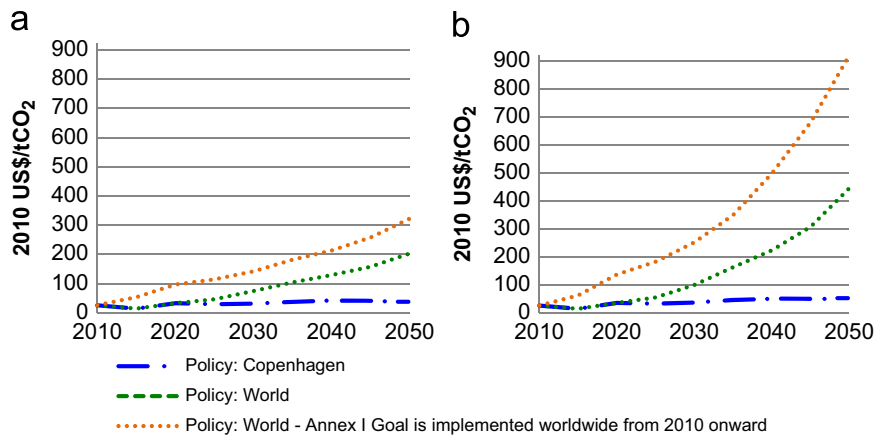


Fig. A2. CO₂ price under different scenarios: (a) biofuels available and (b) biofuels not available.

Appendix A

A1. CTL outputs, crude oil prices, and change in GDP

Table A1 presents the level of CTL adoption, crude oil producer price, and change in GDP under different climate policy scenarios. As mentioned in Section 4, under the *Copenhagen Policy* scenario, it is assumed that USA and other countries who propose their reduction targets (see Table 5) will not enforce them until 2015, 5 years later than other Annex I countries. This explains why in 2010, the negative impacts on GDP almost only happen in Annex I countries exclusively. Besides, in most scenarios, we assume that there is an international carbon market for countries participating in emissions reduction to trade their carbon permits. The only exception is the third scenario *Copenhagen Policy with regional cap-and-trade*, where there is no international carbon market to trade carbon permits. Table A1 shows that the existence of an international carbon market will help China and India mitigating the negative impacts on their GDPs from selling their carbon permits. This is because compared to other countries, if the GDPs of China and India continue to grow, they would have increasing emissions allowances after 2020 due to their emissions intensity targets (see Section 4). In addition, Table A1 shows under the scenario *Copenhagen Policy with regional cap-and-trade*, China would account for most of the CTL output in the world, as mentioned in Section 5. This is because there is no international carbon market to bid up China's domestic low carbon price,⁴ and this allows CTL (without CCS) to become economic in China at higher crude oil prices. Lastly, since before 2025 (see Section 4), the scenario *World Policy* is the exactly the same as the second scenario *Copenhagen Policy with international cap-and-trade*, both scenarios will have the same results in terms of CTL adoption, crude oil producer price, and GDP outcomes in 2010.

A2. Regional CO₂ emissions under different climate policy proposals

Fig. A1 presents the global CO₂ 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 CO₂ allowances to other developed countries and thus curb the CO₂ price, as shown in Fig. A2 in Appendix 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 Fig. A1.

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⁴ Our simulation shows that when there is no international carbon market, China's domestic carbon price would be around \$5/t-CO₂ (2010 price) in 2050.