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Hari Chandan Mantripragada
Carnegie Mellon University

Edward S. Rubin
Carnegie Mellon University, rubin@cmu.edu

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CO_2 reduction potential of coal-to-liquids (CTL) plants

Hari Chandan Mantripragada[a]*, Edward S. Rubin[a]

[a]Department of Engineering and Public Policy, BH 129B, 5000 Forbes Ave, Carnegie Mellon Univerisity, Pittsburgh, PA 15213, USA.

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Abstract

Coal-to-liquids (CTL) processes generate synthetic liquid fuels like gasoline and diesel fuel from coal. Since coal is abundantly available in the U.S., it is widely viewed as a potential source for alternative liquid fuels. One main concern of coal liquids, however, is the huge emissions of carbon dioxide (CO_2) from the CTL process. These emissions can be mitigated using carbon capture and sequestration (CCS) technology in which CO_2 is compressed and sequestered in a geological formation. A comprehensive techno-economic assessment model of liquids-only and poly-generation (producing liquid fuels plus electricity) CTL plants, capable of incorporating CCS is developed. To account for inherent uncertainties and variability, ranges and probability distributions are given to different cost parameters. Finally, the capability of a poly-generation CTL plant in mitigating CO_2 emissions by displacing conventional coal-fired power plants while producing liquid fuels is also investigated.

For a 50,000 barrel/day liquids-only CTL plant using bituminous Illinois#6 coal, capital cost is estimated to be $ 90,300 per daily barrel and the cost of product liquid is about $77/barrel. With the addition of CCS, capital cost increases to about $91,600 per daily barrel and the output cost increases to about $83/barrel. CCS is more cost-effective than paying a carbon tax of as low as $12/ton CO_2. Considering the effects of uncertainties, the 90% confidence interval of output cost is $55 - $97/barrel for a plant without CCS and $62 - $105/barrel for a plant with CCS. The capital cost of a poly-generation plant is about 17% more than that of a liquids-only plant. For the current market prices of electricity, poly-generation plants can produce liquid fuels which are cheaper than those produced from liquids-only plants. A poly-generation plant consumes less coal, and hence is more efficient, compared to separate liquids and power generation plants, with or without CCS. Poly-generation plants also emit less CO_2 than separate liquids and power. However, unless CCS technology is applied, CTL plants will significantly increase emissions of CO_2 relative to conventional oil production. Based on the results from the case study, a few policy implications of large-scale implementation of CTL plants are discussed.
(Units: 1 tonne = 1,000 kg. 1 barrel = 160 litres. All costs are given in constant 2006 dollars).

PACS: Type pacs here, separated by semicolons ;

Keywords: Coal-to-liquids; liquids-only; poly-generation; carbon capture and sequestration (CCS);

* Corresponding author. Tel.: +1-412-268-5607; fax: +1-412-268-3757.
E-mail address: mharichandan@cmu.edu.

1. Introduction

Depleting crude oil reserves and increasing oil prices have stimulated renewed interest in synthetic transportation fuels, such as those derived from coal, to replace or supplement conventional diesel and gasoline. In the most commonly used coal-to-liquids (CTL) technology, coal is first gasified to produce synthesis gas (or syngas) which, in turn, is catalytically treated in a Fischer-Tropsch (FT) process to produce different liquid fuels like gasoline and diesel [1]. These fuels are very clean in terms of criteria air pollutants like nitrogen and sulfur oxides and aromatic hydrocarbons. Since coal is abundantly available in the U.S., it is widely viewed as a potential source for alternative liquid fuels.

Two general configurations of CTL plants are possible as shown in Fig 1. In a typical commercial CTL plant shown in Fig 1(a), the unconverted syngas from the FT reactor is recycled to the reactor to increase the productivity of the liquids. In this paper, such plants are called ‘liquids-only’ plants. Another configuration shown in Fig 1(b), though not yet commercial, is also possible in which the unconverted syngas from the FT reactor, instead of being recycled, is combusted in a gas turbine steam turbine combined cycle power plant to generate electricity. Plants with such a configuration are called ‘poly-generation’ plants in this paper. The by-product electricity can be sold to the grid. Thus, besides providing fuels, CTL technology can also be used for large scale electricity generation.

One main concern of coal liquids is the emissions of carbon dioxide (CO_2) from the CTL process (shown in Fig 1). This CO_2 is usually vented to the atmosphere [2]. As a result, over its life cycle, liquid fuel from coal emits almost double the CO_2 as compared to conventional liquid fuels derived from crude oil [3]. The plant level emissions can be offset by carbon capture and storage (CCS) technology, in which captured CO_2 is compressed and transported to a geological aquifer, where it is sequestered underground. Also, if poly-generation CTL plants can displace conventional coal-fired power plants, there is a possibility of reducing the overall CO_2 emissions. Analysis of technical and economic impacts of this option on the CTL process is the major focus of this paper.

There have been a few recent studies dealing with techno-economic evaluation of CTL plants [4 – 9]. Even though most of the recent studies consider poly-generation facilities, it has to be noted that all of the FT-based synthetic liquid production plants operating commercially today in South Africa are the liquids-only configuration [2]. Poly-generation is still at a conceptual stage and as of now no commercial scale plant of that type has been built. There is little work available on the possible effects of CO2 emission constraints on the cost of poly-generation plants. Also, there is a lack of detailed economic assessments of a CTL plant which systematically analyze the important factors affecting the cost of coal liquids, including the effects of uncertainties in different parameters and the impacts of possible future carbon constraints.

To address these issues, a comprehensive techno-economic assessment model of CTL plants, capable of incorporating CCS and poly-generation options, has been developed. Through an uncertainty analysis, the important factors that affect the cost of liquid fuel production from coal, including the price of coal, economic assumptions, technical factors and carbon constraints are studied. Based on the results of a 50,000 bbl/day case study plant, policy implications of the environmental, economic and strategic aspects of large scale implementation of CTL plants are discussed.

2. The techno-economic model

All the components of the CTL plant, like gasification, gas cleanup, gas upgrade, FT synthesis and power generation were modeled using the Aspen Plus [4] process simulation software. A GE slurry-based gasifier is used to produce syngas from coal. The syngas is cooled and cleaned in a Selexol process in which impurities such as H_2S and CO_2 are separated from the syngas. The clean syngas is fed into a low-temperature (250 ^oC) slurry-based FT reactor using Fe-based catalyst. The CO_2 produced in the FT reactor is separated from the unconverted syngas and other gaseous products using a second Selexol system. The unconverted syngas is either recycled into the FT reactor (liquids-only configuration) or combusted in a gas turbine (poly-generation configuration). In a plant employing CCS, CO_2 from the syngas is separated using an amine-based (MEA) chemical absorption process. The different CO_2 streams are then compressed and transported to a geological sequestration site. Two cases are considered and the incremental costs are compared. For poly-generation plants, the two cases are: (a) capturing only the Selexol-based CO_2 and (b) capturing both the Selexol CO_2 and the MEA CO_2. For a liquids-only plant, electricity is generated only for use within the plant.

For a given capacity of plant and specified operating conditions of different components the model calculates the mass and energy balances of various streams in the process. The results from the performance model are then fed as inputs to a cost model which calculates the capital and operating costs as well as the cost of the liquid product. Equations used to calculate the direct costs of all the process sections, except the Fischer-Tropsch process, are obtained from Integrated Environmental Control Model (IECM) [11]. Cost models for the FT process were developed through regression of cost data from recent literature [6, 9].

In this model, the liquid product from the FT reactor system is considered to be equivalent to crude oil. Production of different liquids in desired proportions requires further refinery processing of these products, which has not been explicitly considered in the process model. All costs are expressed in constant (levelized) 2006 dollars.

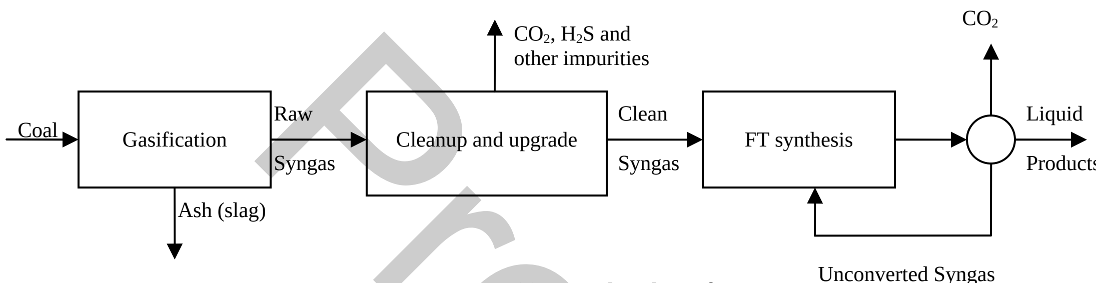

Figure 1 (a): Liquids-only configuration

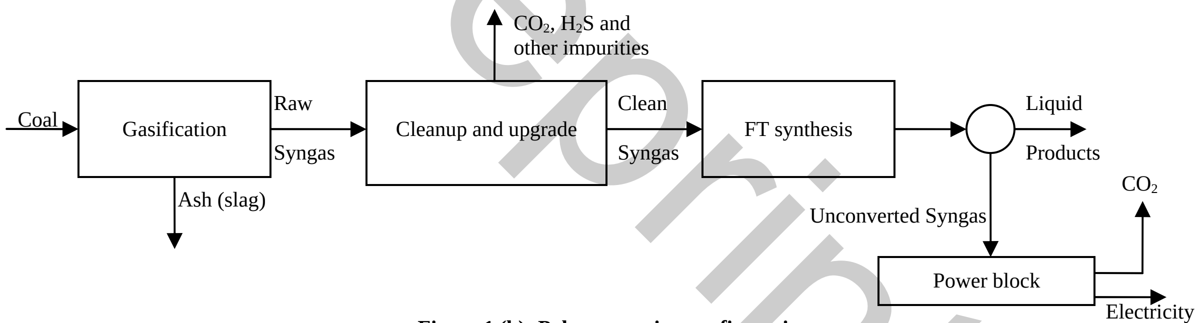

Figure 1 (b): Poly-generation configuration

Figure 1: Two configurations of coal-to-liquids plant: (a) liquids-only plant and (b) poly-generation

3. Case study and results

The techno-economic model was employed for a case study of a liquids-only CTL plant which produces 50,000 barrels/day of liquid fuels using bituminous Illinois #6 coal. Important input and output variables of the model are shown in Table 1. Plant designs with and without CCS were modelled to analyze the effects of a carbon constraint. The model was then applied to a poly-generation plant of the same capacity of liquids output, with and without CCS and with and without carbon constraints. To account for uncertainty and variability, ranges and probability distributions (shown in Table 2) are given to different cost parameters.

Table 1: Important input and output variables of the techno-economic model for the case study plant

Inputs to process model	Outputs from process model (Inputs to cost model)	Outputs from cost model
Plant capacity (50,000 barrels/day, average higher heating value 5,600 MJ/barrel)	Coal flow rate	Specific capital cost ($M/barrel/day)
Type of coal (Illinois#6 bituminous coal, higher heating value 27 MJ/kg)	Syngas generated	Operating cost ($M/year)
Gasifier conditions (1040 ^oC, 43 bar)	CO_2 emissions	Liquid product cost ($/barrel)
Selexol H_2S and CO_2 removal efficiency (99%)	Electricity generated	
Syngas conversion in FT reactor (85%)	Sulfur output	
FT reaction temperature (250 ^oC)		

Table 2: Base case values and uncertainty ranges of important model parameters

Input	Base case value	Uncertainty/Sensitivity range	
Direct capital cost (DC) (all capital equipment of the plant)	Calculated using the outputs of performance model	+/- 10% of base case, ***Triangular [-10%, base case, 10%]***	
General facilities capital (GFC)	15% of DC	10 – 20%	Indirect capital cost – ***Triangular [40, 75, 100]***
Engg & home office (EHO)	10% of DC	7 – 12%	
Process contingency	25% of DC	10 – 40%	
Project contingency	15% of DC	10 – 20%	
Royalty charges	10% of DC	7 – 12%	
Capital recovery factor (CRF) used to annualize capital costs	0.15	5% - 20% (depending on discount rate and plant life) ***Triangular [0.05, 0.15, 0.2]***	
Coal price	$ 60 / tonne	$20 – 100 /tonne [12] ***Uniform [20, 60]***	
Capacity factor (fraction of maximum operation per year)	0.85	0.75 – 0.95 ***Triangular [0.75, 0.85, 0.95]***	
CO_2 transport cost	$ 5 /tonne CO_2	$1.3 – 10.4 /tonne CO_2 ***Uniform [1.3, 10.4]***	CCS O&M costs, from IPCC report [13]
CO_2 storage cost	$ 5 / tonne CO_2	$ 0.65 – 10.4 /tonne CO_2 ***Uniform [0.65, 10.4]***	
Sequestration monitoring cost	$ 0.25 /tonne CO_2	$ 0.13 – 0.39 / tonne CO_2 ***Uniform [0.13, 0.39]***	

3.1 Liquids-only plant results

The results obtained from the techno-economic model are shown in Table 3. The amount of coal needed to produce 50,000 barrels/day of liquid fuel output is about 22,750 tonnes/day and the emissions of CO_2 are about 28,400 tonnes/day. The overall plant efficiency calculated as the energy content of liquid products per unit input energy (based on higher heating value), is close to 48%.

For this plant, capital cost is estimated to be $89,960 per daily barrel and the cost of product liquid is about $77/barrel. It was found that syngas production contributes more than 60% of the capital cost, followed by the FT process (about 20%), then the other sections of the plant. Overall, the capital cost component is a much bigger contributor than operating costs to the total product cost.

In the future, it is likely that there will be an implicit or explicit cost associated with CO_2 emitted into the atmosphere. To see the effect of carbon constraints on the product price a carbon tax of $25/tonne CO_2 was considered. The product cost increased to close to $91/barrel, i.e. an increase of $14/barrel. With or without a carbon price, for these case studies, the product cost is comparable to the recent crude oil prices of $80 - $100/barrel.

With the addition of CCS, capital cost increases to more than $91,000 per daily barrel, an increase of 1.5% and the output cost increases to about $83/barrel, an increase of about 8% from the plant without CCS. Thus, operating costs of CCS affect the output cost of product liquids more than the increase in capital costs. This also shows that having CCS is more cost-effective than paying a carbon tax of $25/tonne CO_2. Calculations show that beyond a CO_2 price of $12/tonne, CCS will be more economical than paying for CO_2 emissions.

Table 3: **Performance and cost results for liquids-only and poly-generation configurations. Both plants produce 50,000 barrels per day of liquid products. All costs in 2006 USD**

	Liquids-only		**Poly-generation**		
Variable	**Without CCS**	**With CCS**	**Without CCS**	**Only Selexol CO2 capture**	**Selexol + MEA CO2 capture**
Coal consumption (tonnes/day)	22,750		25,550		
CO2 emissions (tonnes/day)	28,420	~0	40,560	10,580	1,058
Net power output (MW)	~~	~~	1,090	1,010	960
Efficiency (%, higher heating value)	47.75	46.61	54.19	53.11	52.63
Specific capital cost ($ per daily barrel)	89,960	91,220	108,300	109,600	117,360
Cost of liquid product ($/barrel, $0/tonne CO_2)	76.6	83	(Depends on electricity selling price. Refer Figure #)		
Cost of liquid product ($/barrel, $25/tonne CO_2)	90.8	83			

The deterministic results discussed above show that the cost of liquid product is comparable to the recent crude oil prices of about $100/barrel. However, considering all the uncertainties described in Table 2, Figure 8 compares the output costs for plants with and without CCS when key uncertainties are taken into account. Also shown are the deterministic case costs. The 90% confidence interval of product cost is $55 - $97/barrel for a plant without CCS and $62 - $105/barrel for a plant with CCS. If there is a carbon price, the liquid product from the plant without CCS is in the range of $69 - $111/barrel. Thus, there is uncertainty in whether coal liquids can become economically feasible, given the volatility of crude oil prices being witnessed lately and the potential for future carbon constraints. Also, building CTL plants involves a significant financial risk, owing mainly to the huge capital investments required. For the 50,000 barrel/day plant considered here, the total capital cost is about $4.5 - $6 billion. The risk is that this large investment might become uneconomical should oil prices fall, as they have done in the past.

3.2 Poly-generation plant results

The techno-economic model was also applied to a poly-generation plant of the same liquid product capacity, and the incremental cost of implementing the CCS option by sequestering only the Selexol CO_2, or both the Selexol and MEA CO_2 was estimated. The results are shown in Table 3. Compared to the liquids-only plant, the poly-generation plant uses about 3,000 tonnes/day more coal. Without CCS, it emits close to 12,000 tonnes/day more CO_2. However, Most of these CO_2 emissions can be captured using the CCS option. The overall efficiency of a poly-generation plant is also higher than that of liquids-only plant because of the additional electricity produced.

It can be see that without CCS, the capital cost of a poly-generation plant is about 17% more than that of a liquids-only plant. To capture only the Selexol CO_2, capital cost increases only slightly, but when CO_2 from both the Selexol and MEA is captured, the capital cost increases by about 8%.

The cost of product liquids from a poly-generation plant depends on the revenue generated from electricity sales. Figure 2 shows the effect of electricity selling price on the cost of product liquids for cases where there is no CCS and with CO_2 captured from both Selexol and MEA (with and without a carbon tax of $25/ton of CO_2). The electricity price at which poly-generation breaks even with a liquids-only plant (based on the cost of liquid products) is shown with arrows. For all the cases, poly-generation plants become cheaper than liquids-only plants when the selling price of electricity is in the range of 2 – 5 cents/kWh. This price range corresponds approximately to current market prices of electricity. However, such prices can be expected to grow when there are carbon constraints. In effect, the results show that poly-generation plants can produce liquid fuels which are cheaper than those produced from liquids-only plants.

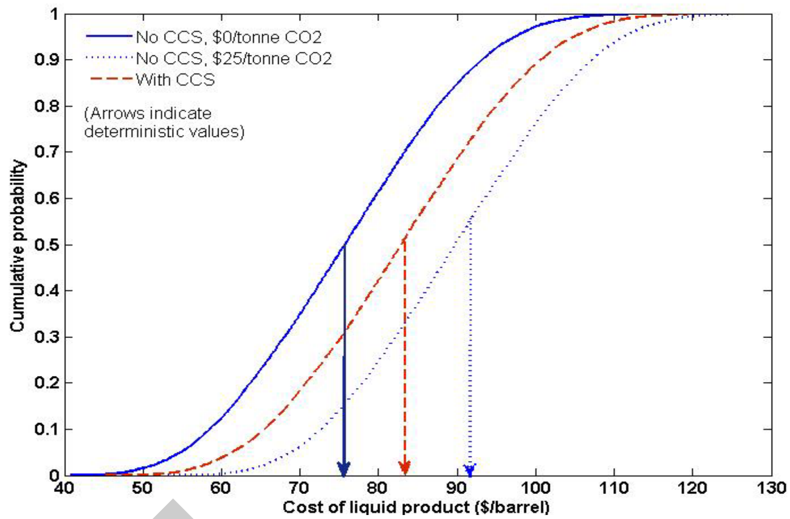

Figure 2: Comparison of costs of liquid products from plants without and with CCS, including the effect of uncertainty. Arrows indicate deterministic values.

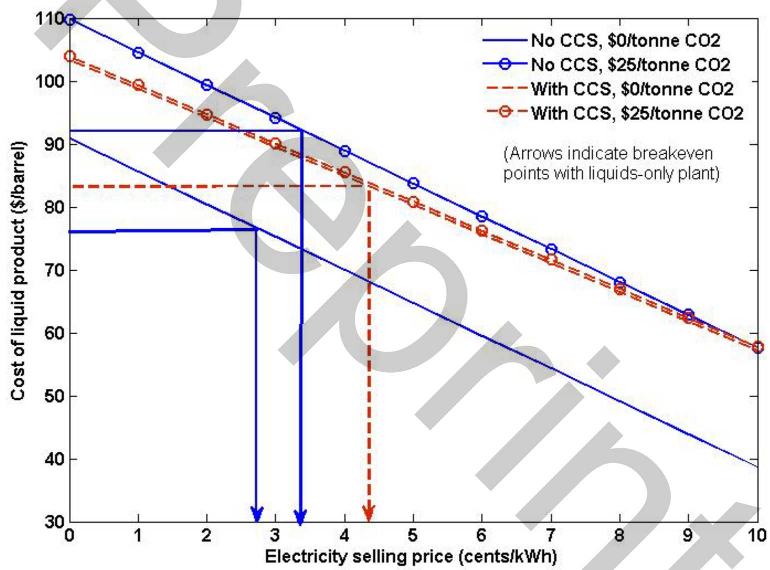

Figure 3: Effect of selling price of electricity (cents/kWh) on the cost of liquid product from a poly-generation CTL plant. Arrows show the prices at which poly-generation breaks even with liquids-only plants in terms of cost of liquid products.

4. The potential of poly-generation plants to mitigate CO_2 emissions

One possible advantage of a poly-generation type plant might be its usefulness in displacing electricity from conventional coal-fired power plants. To examine this hypothesis, a poly-generation plant producing both liquid fuels and electricity has been compared to a separate liquids-only plant plus a conventional coal-fired power plant which produces only electricity. Two types of power plants are considered: pulverized coal combustion (PCC) and integrated gasification combined cycle (IGCC) plants. As seen in Table 3, a poly-generation plant produces close to 1000 MW of electricity with or without CCS, along with the production of 50,000 barrels per day of liquid fuels. This is compared to a liquids-only CTL plant which produces 50,000 barrels per day of liquid fuels plus the conventional PCC or IGCC power plant producing 1000 MW with and without CCS respectively. The results for power plants were obtained from the IECM computer model [11].

A comparison of these three cases is shown in Fig 4. It can be seen that poly-generation of liquids and electricity consumes much less coal and emits less CO_2 than separate generation of liquids and power. This holds true for cases with or without CCS. This, if CTL is seen as a potential source of liquid fuels, then it can be argued that the poly-generation option is more efficient and results in lower CO_2 emissions than liquids-only plant, provided conventional coal-fired power plants are displaced at the same time.

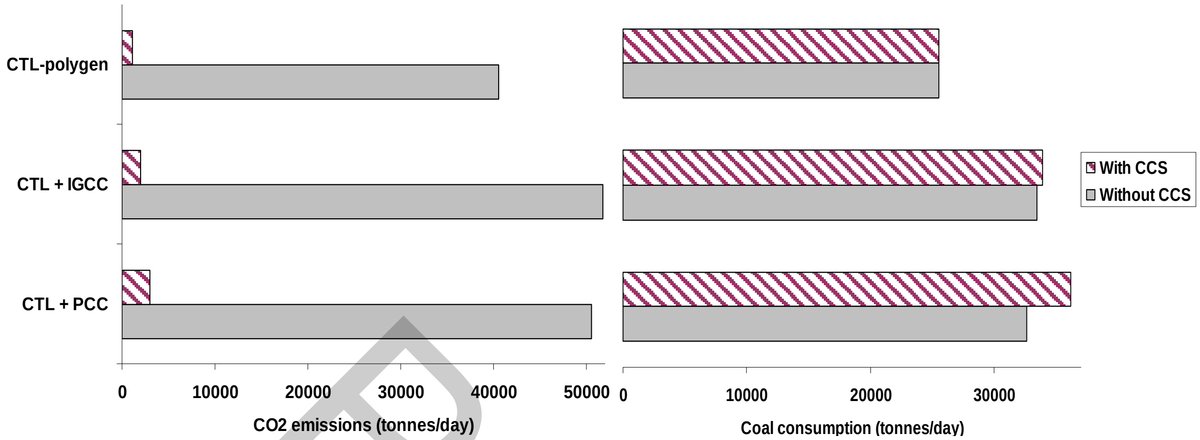

Figure 4: Comparison of coal consumption in poly-generation CTL plants with separate liquids-only and conventional coal power plants. Poly-generation consumes less coal than separate production, with and without CCS

The efficacy of the poly-generation option is further illustrated with the help of the following simplified calculation. In 2006, US petroleum consumption was about 20 million barrels/day. As an upper bound, if CTL were to meet this requirement, there would have to be about 400 plants of 50,000 barrels/day. The assumption implicit in this is that coal liquids can be reformed into any type of liquid fuel desired. The total CO_2 emissions from 400 liquids-only CTL plants would be about 3.5 billion tons/year. This would be a 60% increase in current overall CO_2 emissions in the U.S., which were 5.9 billion tons in 2006 [12]. Even if CCS technology were employed, emissions from combustion of coal liquids in automobiles and other transport vehicles still would remain. Thus, CTL is not a solution to the growing threats of global warming, which requires a net reduction in overall emissions.

In contrast to liquids-only plants, poly-generation plants have a potential to mitigate CO_2 emissions. But this is possible only if conventional coal-fired power plants are displaced by poly-generation CTL plants with CCS. For example, 400 poly-generation plants with CCS of the type shown in Table 7 would emit roughly about 0.2 billion tons CO_2 per year, but would displace 400,000 MW, almost the whole of conventional coal plant capacity, emitting about 3 billion tonnes/year of CO_2. Apart from providing roughly half the current U.S. electricity generation, this would yield a net reduction in CO_2 of roughly 2.8 billion tons/year or nearly 50% of current U.S. emissions. Though this scenario is purely hypothetical, it illustrates that poly-generation CTL plants employing CCS have the ability to achieve significant net reduction in national CO_2 emissions.

Coal-derived liquids also are inherently much cleaner than conventional fuels [2] in terms of criteria air pollutants. Coupled with the CO_2 reduction possible as described above, use of coal liquids thus yields to important environmental benefits, in terms of end use. However, unless CCS technology is proven to be commercial, on a large-scale, CTL plants will lead to significant increase in CO_2 emissions, roughly 40% of the current annual CO_2 emissions in the U.S. There will also be added environmental risks associated with plant operation and with increased coal consumption. At the same time, implementing CTL on a large scale offers important strategic benefits by increasing the energy security of countries like the U.S. which have large coal reserves. However, as seen in the previous sections, coal liquids might not be economically feasible under all conditions. Thus, the environmental, economic and strategic risks of CTL technology have to be addressed simultaneously before making any decisions regarding its large-scale implementation, as pointed out by Farrell and Brandt [3].

7. Conclusions

A techno-economic assessment of a coal-to-liquids (CTL) plant was performed to analyze the effects of different design parameters and carbon mitigation measures on the cost of product liquid fuels. Coal liquids, produced either from a liquids-only plant or a poly-generation plant, can be competitive in the current world of high (~ $100/barrel) crude oil prices, even with implementation of CCS. CCS proved to be more cost-effective than paying a carbon tax of as low as $12/ton CO_2. It was found that the poly-generation capability of CTL plants can be utilized to co-produce electricity and to mitigate CO_2 emissions by displacing conventional coal-fired power plants. However, unless CCS technology is proven to be commercial on a large-scale, CTL plants will lead to major increases in emissions of CO_2. Also, apart from the advantages CTL offers as a source of alternative transportation fuels, the environmental, economic and strategic dimensions of large scale implementation of CTL have to be addressed simultaneously to inform decisions regarding its use.

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