Memo to: Steve Koonin
From: Bob Williams
Subject: Addressing CO_2 emissions from coal power and transportation via EOR applications for CO_2 captured from coproduction systems that coprocess fossil fuel and biomass

This memo is background for comments I hope to make at the QTR meetings on 7 and 8 June in Boulder.

In the memo I sent you as a QTR input on alternative low-C fuels on 25 April 2011 I discussed the prospective economics of systems that coproduce liquid transportation fuels and electricity from coal and biomass with CCS from the perspective of synthetic fuel providers. At the electricity QTR meetings in Boulder on 7 and 8 June one focus of my remarks will be on these systems that coprocess fossil fuel (coal or natural gas) and biomass with the economics presented from the perspective of electricity generators, with emphasis on EOR applications of the captured CO_2.

Such hybrid strategies providing electricity, liquid fuels, and CO_2 for EOR via coprocessing fossil fuel and biomass offer considerable technical and economic promise (LIU et al, 2011) but are inherently hard for DOE to pursue because stovepiping constraints makes it difficult for the culturally different DOE divisions to collaborate to help bring such technologies into the market. The QTR Framing document refers only parenthetically (on page 25) to coal and biomass coprocessing—but not to natural gas and biomass coprocessing (LIU et al., 2010), not to options for the coproduction of synfuels and electricity, and not to CO_2 EOR. Furthermore, there is no discussion of CCS for biomass-based systems—which can be very important to system economics under a carbon policy constraint—as I showed in my 25 April 2011 submission to the QTR process.

The categorization of options into the six strategies shown in Figure 2 of the QTR framing document virtually precludes serious consideration of hybrid strategies that involve the coproduction of transportation fuels and electricity. Leadership at high levels in DOE and The Administration is needed to overcome these organizational obstacles that stand in the way of substantial technological innovation that could be realized even during this decade with technologies near at hand.

One of the main US challenges relating to electric power is decarbonizing existing coal power plants, which account for ~ ½ of US power generation and ~ 1/3 of CO_2 emissions from fossil fuel burning. Coproduction systems are economically attractive repowering alternatives compared to CCS retrofits of existing coal power plants and alternative repowering systems (Williams et al., 2010).

Coproduction systems coprocessing < 10% biomass can be deployed during this decade in CO_2 EOR applications using technologies that are commercially ready or near commercial. A CBTL-OTA-CCS-5%[1] coproduction system for which ~ 70% of the output is FTL fuels and ~ 30% of the output is electricity, which captures ~ 65% of the CO_2 in the feedstock, would have a fuel cycle wide GHG emission rate < ½ of that for the fossil energy displaced (see Table 1, Table 2, and Figure 1).

[1] Acronyms for systems described in this memo are defined in Table 1.

Coproduction systems are characterized by CO_2 capture costs that are much lower than for stand-alone power plants (LIU et al, 2011). Consider that if the plant gate selling for a CBTL-OTA-CCS-4.9% plant were only $7/t, its levelized cost of electricity (LCOE) at zero GHG emissions price would be the same as for a CTL-OT-V plant (see Figure 2). In a competitive market the plant owner would be willing to sell CO_2 for prices that approach this level, which implies that the CO_2 could be transported to markets as far away as ~ 2000 km and the CO_2 would still be competitive in EOR markets: As shown in Figure 3, the delivered cost at such a distance would be $20-$30 a tonne; for comparison the price in current CO_2 EOR markets is $25 to $40 a tonne. This suggests that coproduction systems deployed as repowering options at most existing coal power plant sites could plausibly serve EOR markets, however remote.

Second generation (post-2020) coprocessing technology that coprocesses ~ 30% biomass (CBTL-OTA-CCS-29%--see Figure 4) would be able to realize > 90% reduction in GHG emissions for both liquid fuels and electricity. For such systems a minimum plant-gate CO_2 selling price of $0/t CO_2 could be realized for a GHG emission price of $25/t CO_{2eq}—see Figure 6. Such plants that are able to sell CO_2 for $7/t can provide decarbonized electricity that is no more costly than electricity from a written off coal plant @ $0/t CO_{2eq} in a world with $100 a barrel oil prices (compare Figures 5 and 6) .

What is the magnitude of the CO_2 EOR opportunity? The US technical potential for CO_2 EOR is comparable to that for oil on the US Outer Continental Shelf. A soon-to-be released study[2] suggests that CO_2 EOR could plausible provide, beyond what is already planned, an additional 4 million barrels per day of incremental crude. If this much incremental crude oil were provided WAG (@ 0.35 tonnes of purchased CO_2 per incremental barrel) entirely from CBTL-OTA-CCS-29% CO_2 sources, ~ 40 GW_e of CBTL-OTA-CCS-29% capacity would be required—an amount that would displace ~ 75 GW_e of existing coal capacity,[3] assuming that a CBTL-OTA-CCS-29% plant would have a coal input capacity that is about the same as for the old coal power plant displaced. The gasoline-equivalent liquid fuels provided via EOR would amount to 3.9 million barrels per day and another 1.5 million barrels per day would be provided in the form of FTL fuels. GHG emissions would be reduced more than 90% for the electricity and FTL fuels. The GHG emissions for all the liquid fuels produced (CO_2 EOR products as well as FTL fuels) would be ~ ¼ less than for crude oil products. The biomass required by 2030 would be ~ 140 million tonnes per year. The CO_2 delivery rate in 2030 from these plants would be ~ 500 million tonnes per year (much of which would be photosynthetic CO_2).

This CO_2 EOR opportunity coupled to low-cost CO_2 capture technologies such as coproduction systems makes it feasible to move forward aggressively with CCS technologies even in the absence of a stringent carbon mitigation policy and buys decades of time to sort out and resolve remaining technical challenges associated with CO_2 storage in deep saline formations before having to widely exploit such storage options. Moreover, if these coproduction technologies are deployed mainly as repowering options at sites of existing coal power plants, rapid capacity

[2] Kuuskraa, V.A., Tyler van Leeuwen, and Matt Wallace, Improving Domestic Energy Securityt and Lowering CO_2 Emissions with "Next Generation" CO_2-Enhanced Oil Recovery (CO_2-EOR)Tyler, draft final report prepared for the National Energy Technology Laboratory by Advanced Resources International, 1 June 2011.

[3] For comparison, EIA (AEO 2011) estimates that up to 73 GW_e of existing coal generating capacity may be retired as by 2035 a result of EPA environmental regulations (exclusive of regulations relating to carbon mitigation).

growth should be feasible, because permitting should be much easier than for building new plants at greenfield sites.

There is now wide recognition in the global integrated assessment community that the cost of realizing carbon mitigation goals would be substantially less if CCS for biomass energy systems is included in the portfolio of carbon mitigation options.[4] CCS for biomass energy warrants high priority in light of the huge C-mitigation benefits offered by exploiting the negative GHG emissions benefit of photosynthetic CO_2 storage and the powerful economic benefits offered by such systems under a C-mitigation policy. Coproduction plants that coprocess coal and biomass with CCS would be able compete very effectively with alternative biomass CCS options up to very high GHG emissions prices (see Figure 7).

Coal/biomass to liquids and electricity with CCS represents an attractive strategy for launching CCS for biomass energy in the market. Focusing on coal/biomass coprocessing now could be a bridge to a much wider global effort, perhaps in the post-2030 period, when biofuels such as FTL with CCS derived from only biomass with CCS could become cost competitive with crude oil products in the many biomass-rich but coal-poor regions of the world—if the global community eventually enacts a serious carbon mitigation policy and thereby prices carbon to make such technologies attractive (as I showed in my 25 April 2011 low carbon fuels submission to the QTR process).

The strong negative emissions of such biomass energy systems with CCS and the fact that coal/biomass systems with CCS enable deep reductions in GHG gases for transportation fuels with < 40% as much biomass as conventional next-generation biofuels (as I showed in my 25 April 2011 low carbon fuels submission to the QTR process) imply that, in principle at least, it is feasible to realize deep reductions in GHG emissions for transportation without abandoning oil and without having to use cropland for growing dedicated energy crops—thereby largely avoiding conflicts with food production and direct and indirect land-use impacts. A global transportation thought experiment is presented in Figure 8 to illustrate this point. This thought experiment [from the forthcoming *Global Energy Assessment* (Larson and LI et al., 2011)] is described in the appendix.

Coproduction technologies that coprocess coal and biomass with CCS, though attractive environmentally and economically, face institutional obstacles as a result of having to provide products for three very different commodity markets (for transportation fuels, electricity, and CO_2) and having to manage two very different feedstocks (coal and biomass). It is unclear what entities would own and operate such systems.

[4] See, as examples: (i) Karlsson, H., and Bystr□m (Biorecro AB), 2011: *Global Status of BECCS Projects*, a report prepared for the Global CCS Institute, Canberra, Australia, March; (ii) Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vurren, D.P., den Elzen, K.M.G.J, M□llersten, K., and Larson, E.D. 2010: The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Clim. Change*. 100: 195-202; and (iii) Luckow, P., Dooley, J.J., Wise, M.A., and Kim, S.H. 2010: *Biomass Energy for Transport and Electricity: Large Scale Utilization Under Low CO_2 Concentration Scenarios*, Report PNNL-19124 prepared for the US Department of Energy, January.

Moreover, these technologies are largely unknown to most stakeholder groups. They cannot go forward unless commercial scale demonstration projects are carried out, and DOE resources for needed demo projects are scarce.

In his exchanges with Senator Manchin and Congressman Shimkus in Senate and House hearings on the DOE budget during February and March, Secretary Chu expressed the Administration's strong interest in advancing the coal/biomass to liquids with CCS concept. However, this stated interest is at odds with the current DOE budgetary stance of the Administration: According to the QTR Framing Document, "DOE currently has no activities related to liquid transportation fuels from fossil feedstocks." Will this situation be turned around when it comes to be recognized that coal/biomass coprocessing with CCS represents an economically attractive path to deep reductions in GHG emissions for transportation fuels?

Table 1: Acronyms defined	
FTL fuels	Fischer-Tropsch liquid fuels (diesel/jet and gasoline)
BTL	Coal + biomass to finished FTL fuels and electricity
CBTL	Coal + biomass to finished FTL fuels and electricity
BIGCC	Biomass integrated gasifier combined cycle power plant
CBIGCC	Coal/biomass integrated gasifier combined cycle power plant
RC	FTL synthesis with recycle (RC) of unconverted syngas to maximize FTL output
OT	FTL synthesis with once through (OT) synthesis; unconverted syngas is burned to make coproduct power in combined cycle power plant ("mild capture" of naturally concentrated CO_2 in syngas)
OTA	Autothermal reformer (A) and extra CO_2 capture equipment added to OT system (downstream of synthesis) to increase CO_2 capture/storage ("aggressive capture")
V	Coproduct CO_2 is vented
CCS	Coproduct CO_2 is captured and piped to underground storage site
X%	Percent biomass (energy basis) that is coprocessed with coal

Table 2: Features of alternatives to a written off pulverized coal power plant

Technology		Energy output capacities		CO_2 captured, 10^6 t/y (% of feedstock C stored as CO_2)	Biomass use, 10^6 t/y (% of input, HHV)	TPC (overnight construction cost—N[th] plants), $\$10^6$
	GHGI[c]	FTL Fuels, barrels/day	Electricity, MW_e			
WO PC-V[a]	1.00	0	543	0	0	0
PC-CCS retrofit[a]	0.19	0	398	3.5 (90)	0	426
CTL-OT-V[b]	1.17	15,500	543	0 (0)	0	2190
CBTL-OTA-CCS-4.9%[b]	0.46	22,500	543	7.5 (65)	0.35 (4.9)	3260
CBTL-OTA-CCS-29%[b]	0.077	10,900	287	3.7 (65)	1.0 (29)	1790

[a] For details see Williams et al. (2010).
[b] For details see Liu et al. (2011).
[c] GHGI (greenhouse gas emissions index) ≡ (system-wide GHG emissions for production + consumption of energy products)/(system-wide GHG emissions for fossil energy displaced). For the calculations in this table it is assumed that the displaced fossil fuel-based electricity is that from the written off coal plant that vents CO_2 and that the displaced liquid fuels are the crude oil-derived equivalents of the Fischer-Tropsch diesel and gasoline produced.

Table 3: Features of systems using 0.46 x 10^6 tonnes of biomass annually & storing CO_2

Technology	Physical metrics			Energy outputs		% of C in feedstock stored as CO_2	TPC (overnight construction cost—N[th] plants), $\$10^6$
	GHGI[c]	BII[d]	ZEFI[e]	Fuels, barrels/day of gasoline equivalent	Electricity, MW_e		
BTL-RC-CCS[a]	- 0.95	2.15	1.02	2,240	14.2	56	416
CBTL-OTA-CCS-29%[a]	0.086	0.90	0.92	5,400	131	65	939
BIGCC-CCS[b]	- 0.93	-	0.99	0	118	90	398
CBIGCC-CCS-39%[b]	- 0.34	-	0.80	0	260	90	1006

[a] For details see Liu et al. (2011).
[b] For details see Larson and Li (2011).
[c] GHGI (greenhouse gas emissions index) ≡ (system-wide GHG emissions for production + consumption of energy products)/(system-wide GHG emissions for fossil energy displaced). For the calculations in this table it is assumed that the displaced fossil fuel-based electricity is that from a new supercritical coal plant that vents CO_2 and that the displaced liquid fuels are the crude oil-derived equivalents of the Fischer-Tropsch diesel and gasoline produced.
[d] BII (biomass input index) ≡ GJ of dry biomass required to manufacture 1 GJ of liquid fuel (LHV basis).
[e] ZEFI (zero-emissions fuels index) ≡ total GJ of net zero GHG-emitting liquid fuel provided per GJ of biomass input via production and/or offsets of crude-oil-derived products.

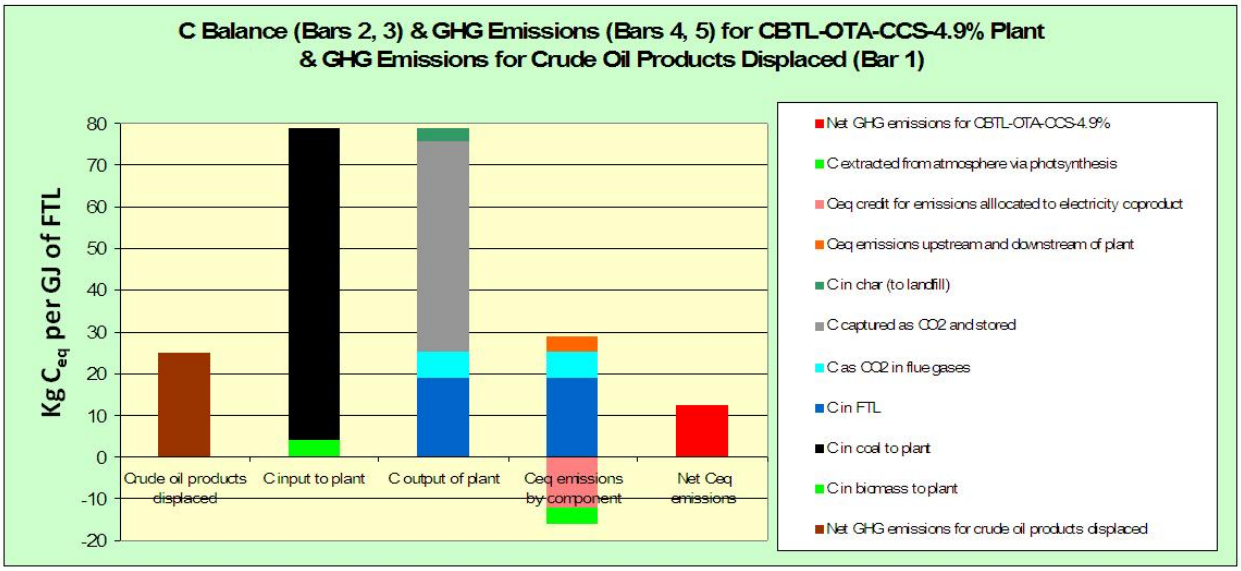


Figure 1: Carbon Balance & GHG Emissions for CBTL-OT-CCS-4.9% System in Table 2

For this plant GHGI = 0.46. It is assumed that the GHG emissions allocated to electricity are for a NGCC plant that vents CO_2 (115 kg C_{eq}/MWh) and that the rest of the emissions are allocated to FTL fuels = 0.50 X [emission rate for crude oil products displaced (25.0 kg C_{eq}/GJ)] = 12.5 kg C_{eq}/GJ.

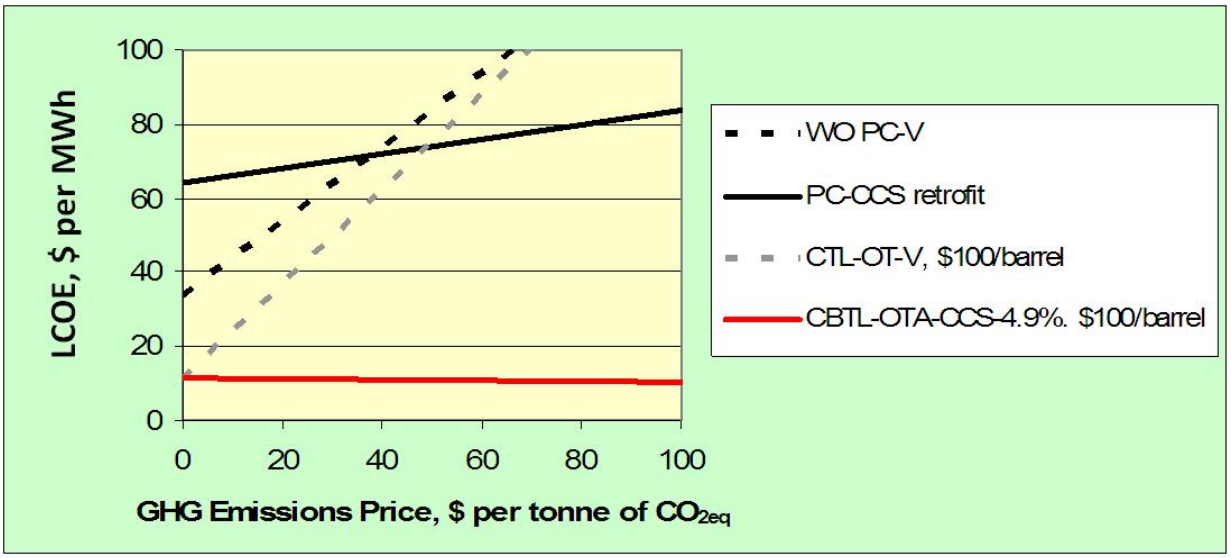
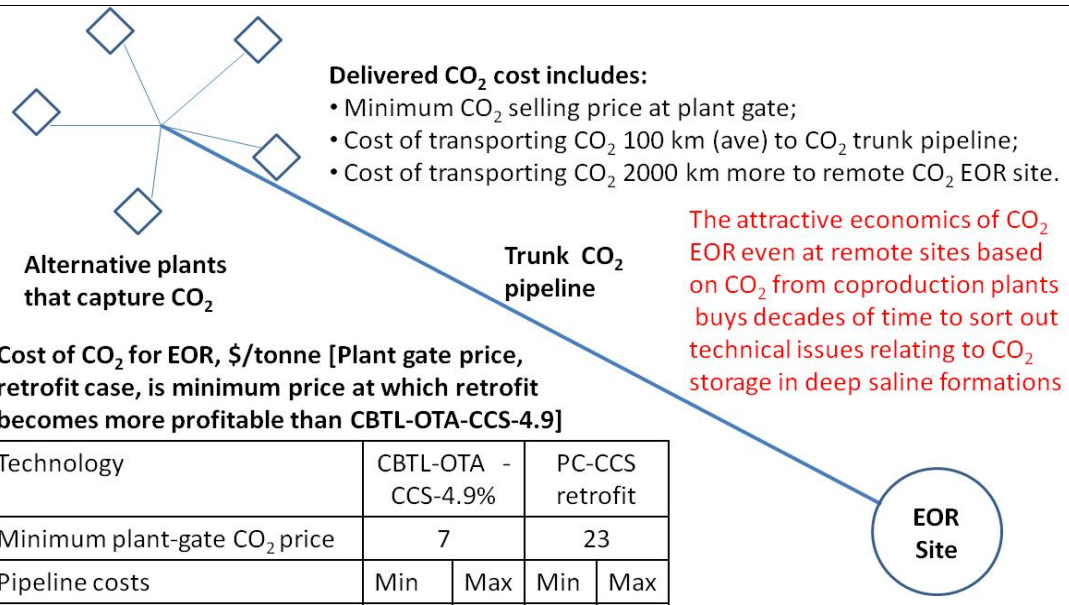


Figure 2: Levelized Cost of Electricity (LCOE) for Some Energy Systems in Table 2 if Captured CO_2 Is Used for Enhanced Oil Recovery (EOR)

It is assumed for this construction that the plant-gate CO_2 selling price = $7/t—the value needed to make the LCOEs equal for CBTL-OTA-CCS-4.9% and CTL-OT-V at zero GHG emissions price.



Cost of CO_2 for EOR, $/tonne [Plant gate price, retrofit case, is minimum price at which retrofit becomes more profitable than CBTL-OTA-CCS-4.9]

Technology	CBTL-OTA - CCS-4.9%		PC-CCS retrofit	
Minimum plant-gate CO_2 price	7		23	
Pipeline costs	Min	Max	Min	Max
100 km	0.7	1.2	1.1	1.8
Trunk pipeline (2000 km)	13	22	19	33
CO_2 cost at EOR site	**21**	**30**	**43**	**58**

Figure 3: Cost CO_2 at EOR Sites Remote from Coproduction Plants

Coproduction systems such as CBTL-OTA-CCS-4.9% would be highly competitive in EOR markets that are remote from energy conversion plants because of the ultra-low CO_2 capture costs for such plants.

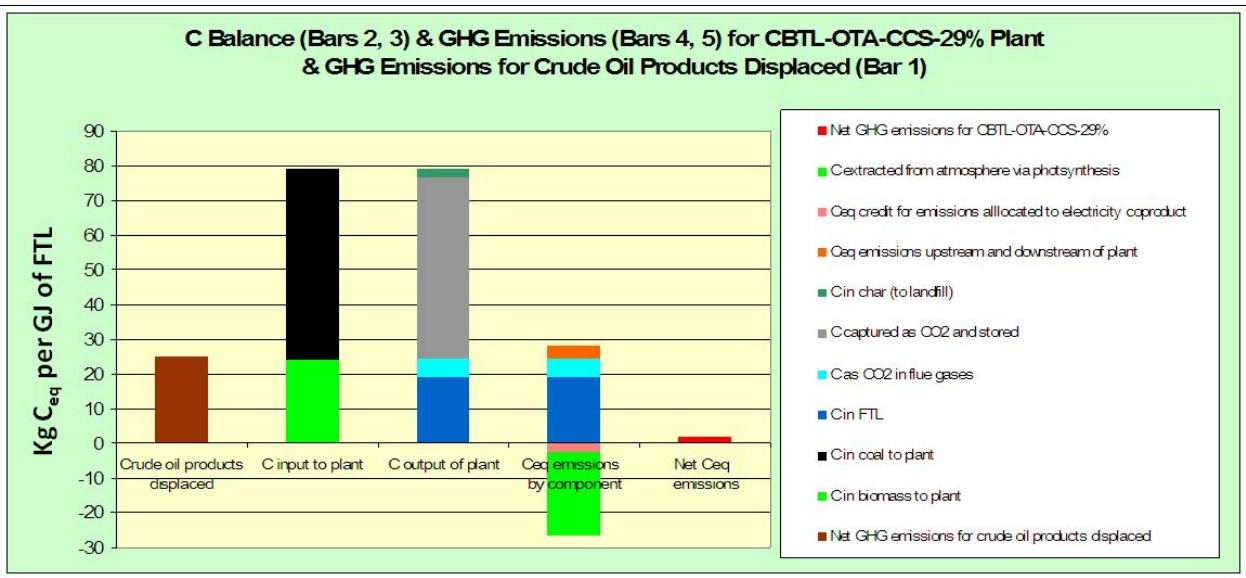


Figure 4: Carbon Balance & GHG Emissions for CBTL-OT-CCS-29% System in Table 2 2

For this plant GHGI = 0.077. It is assumed that emissions are reduced by the same percentage for FTL & electricity according to GHGI. Thus FTL fuels emission rate = 0.077*(25.0 kg C_{eq}/GJ, for crude oil products displaced) = 1.9 kg C_{eq}/GJ, and electricity emission rate = 0.077*(273 kg C_{eq}/MWh, for displaced coal plant) =21.1 kg C_{eq}/MWh.

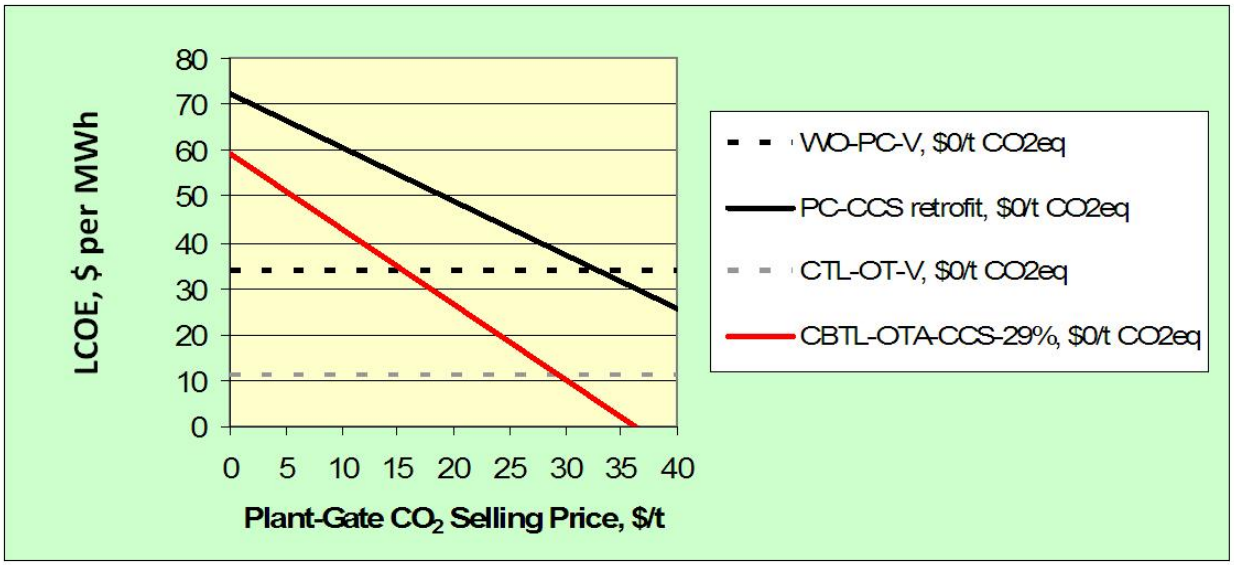


Figure 5: LCOE for Some Energy Systems in Table 2 If Captured CO_2 Is Used for EOR

It is assumed that: coal and biomass prices are $2.0/GJ and $5.0/GJ (HHV basis), respectively; $100/barrel crude oil price; $0/t CO_{2eq} GHG emissions price.

The CO_2 selling price at with the CTL-OT-V and CBTL-OTA-CCS-29% curves cross ($30/t) might be considered the minimum CO_2 selling price for a CBTL-OTA-CCS-29% system at zero GHG emissions price. The CO_2 selling price at with the WO PC-V and PC-CCS retrofit curves cross ($33/t) might be considered the minimum CO_2 selling price for a PC-CCS retrofit system at zero GHG emissions price.

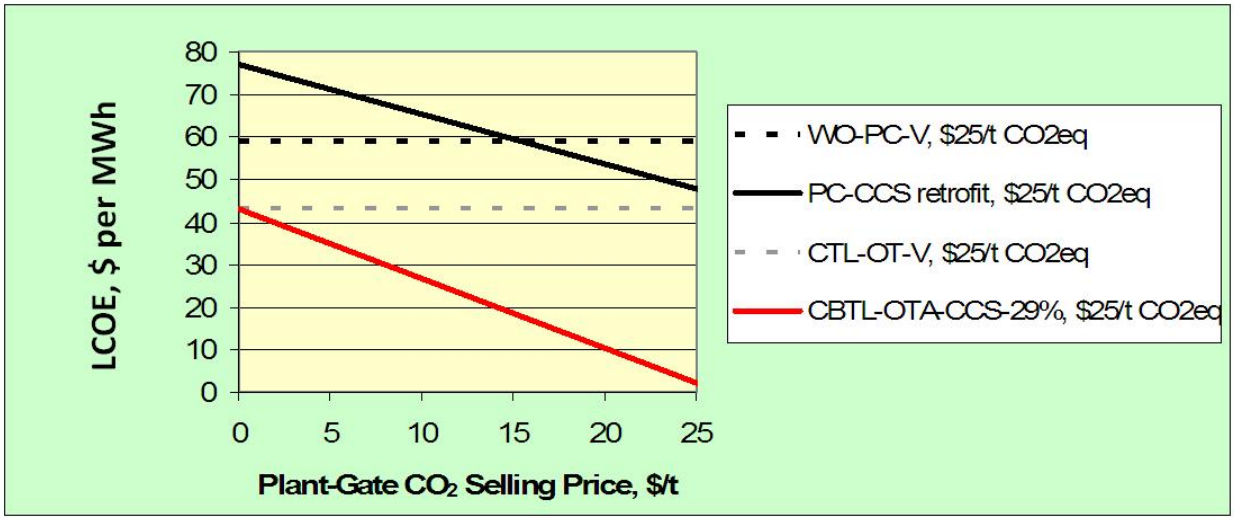


Figure 6: LCOE for Some Energy Systems in Table 2 If Captured CO_2 Is Used for EOR

It is assumed that: coal and biomass prices are $2.0/GJ and $5.0/GJ (HHV value basis), respectively; $100/barrel crude oil price; & a $25/t CO_{2eq} GHG emissions price—a price high enough to make the CTL-OT-V and CBTL-OTA-CCS-29% curves cross at a CO_2 selling price of $0/t—which might be considered the minimum CO_2 selling price for a CBTL-OTA-CCS-29% system at the assumed GHG emissions price. The CO_2 selling price at which the WO PC-V and PC-CCS retrofit curves cross ($16/t) might be considered the minimum CO_2 selling price for a PC-CCS retrofit system at a GHG emissions price of $0/t.

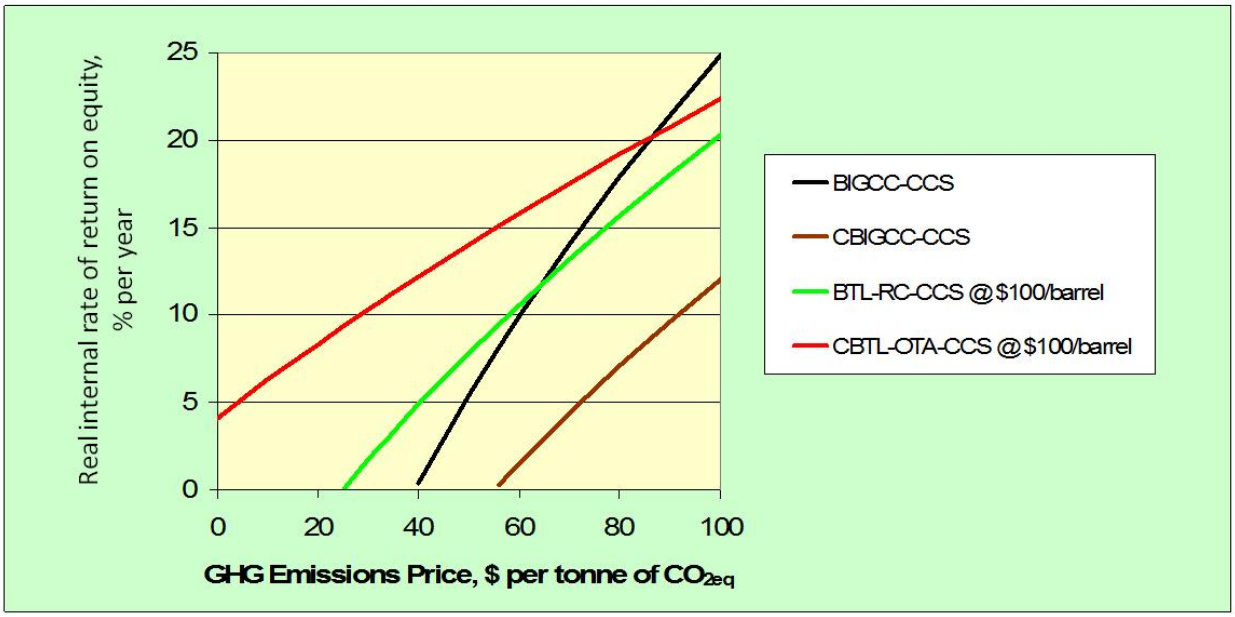


Figure 7: Real Internal Rate of Return on Equity for Alternative Biomass-Using Energy Systems with CCS

The options compared are described in Table 3. The assumed coal and biomass prices are $2.0/GJ and $5.0/GJ (HHV value basis), respectively. It is assumed that the CO_2 is stored in deep saline formations.

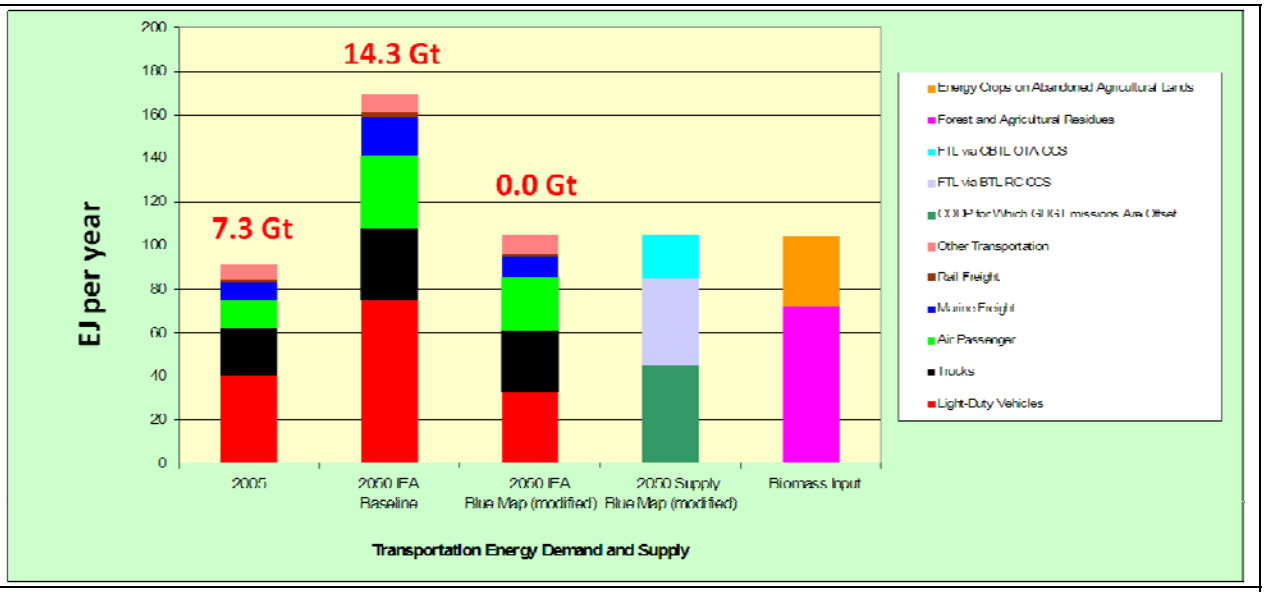


Figure 8: Energy and GHG Emissions for Coal/Biomass Thought Experiment for Global Transportation and for IEA 2050 Base-Line (Business as Usual) Scenario

Numbers at tops of bars are total GHG emissions in Gt CO_{2eq} per year.

This figure is the same as Figure 12.66 in the Appendix.

References

Larson, E.D., and LI, Zheng (Co-Convening Lead Authors), Fleisch, Theo, LIU, Guangjian, Nicolaides, G., REN Xiangkun, and Williams, R.H.: "Knowledge Module 12: Fossil Energy Systems," *The Global Energy Assessment*, Cambridge University Press, Cambridge, UK, 2011 (forthcoming).

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Williams, R.H., Guangjian LIU, T.G. Kreutz and E.D. Larson, "Alternatives for Decarbonizing Existing USA Coal Power Plant Sites," *10th International Conference on Greenhouse Gas Technologies (GHGT-10)*, Amsterdam, Sept. 19-23, 2010.

Appendix: Global Coal/Biomass Thought Experiment for Transportation

This appendix is the final draft of a subsection (12.7.6) of "Knowledge Module 12: Fossil Energy Systems" of the forthcoming *Global Energy Assessment* report (Larson and LI et al., 20111)

A global coal/biomass thought experiment (Global C/B TE) for transportation is presented to illustrate the C-mitigation potential for transportation at midcentury via widespread use of low-C fuels provided via coal and/or biomass with CCS in many regions—coal-poor (via BTL-RC-CCS) as well as coal-rich (via CBTL-OTA-CCS)— but for a world in which the growing of dedicated energy crops on cropland is off-limits (Tilman et al., 2009) because of concerns about impacts on food prices (Rosegrant, 2008) and land-use effects (Fargione et al., 2008; Searchinger et al., 2008).

It is assumed for the supply side of the Global C/B TE that the only biomass supplies are residues[5] and mixed prairie grasses grown with minimal inputs on abandoned agricultural lands. The estimated total global biomass supply under these conditions is approximately 6 billion dry tonnes per year[6]—all of which is assumed to be used in the Global C/B TE. It is assumed that worldwide CBTL-OTA-CCS plants use 1 billion tonnes per year of biomass and that the rest of the biomass is used in BTL-RC-CCS plants located in coal-poor regions. Many of these plants would be located in developing regions—e.g., in sub-Saharan Africa and Latin America.

Dedicating the entire global biomass supply to the Global C/B TE is clearly an unrealistic assumption. However, these applications are likely to be hard to beat in terms of both the carbon mitigation per tonne of scarce biomass and economics in a world of high GHG emissions prices and oil prices. Moreover, such a starkly defined Global C/B TE helps to clarify the tradeoffs associated with the allocation of scarce biomass resources.

The demand for global transportation energy in 2050 in the Global C/B TE is assumed to be essentially that presented for the IEA's Blue Map Transportation Scenario (IEA, 2009)—an update of the IEA Blue Map Projection to 2050 in IEA (2008). [7] A general characterization of the IEA Blue Map Scenario is that it envisages technological change consistent with realization by mid-century of a 50% reduction in global GHG emissions relative to 2005—including a strong emphasis on improving energy efficiency but excluding lifestyle changes and modal shifts. Assuming an energy-efficient future as a context for exploring the prospects for carbon mitigation via biomass and coal with CCS is appropriate because typically energy efficiency improvement represents the low-hanging fruit in carbon mitigation and thus should be a priority for exploiting.

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[5] Agricultural residues, forest residues, forest thinnings to reduce forest fire risk and enhance productivity for commercial species, urban wood wastes, municipal solid wastes.

[6] In energy terms, the residue supply is assumed for 2050 to be 75 EJ per year [the global residue supply for energy assumed for 2050 in (IEA, 2008)]. The assumed potential supply of biomass grown on abandoned agricultural lands is 32 EJ per year (average yield of 4.3 dry tonnes per year on 429 million hectares worldwide) based on (Campbell et al., 2008). The total biomass supply is 2.3 X total biomass use for energy in 2005. For comparison, the global biomass supply for 2050 in the IEA Blue Map scenario is 150 EJ/year (which includes biomass grown for energy on cropland). For perspective, the total assumed global biomass supply (107 EJ per year) is comparable to total US primary energy consumption in 2006 (97 EJ per year).

[7] For the IEA Baseline Projection the total number of light-duty vehicles (LDVs) increases 3X to 2.15 billion, 2005-2050, air travel increases 3.9 X, and truck freight increases 1.9 X.

The IEA Baseline Projection (involving nearly a doubling of both energy demand and GHG emissions) shown in Figure 12.1 illustrates the dimension of the challenge for global transportation—which is to reduce GHG emissions at midcentury by a factor of four relative to

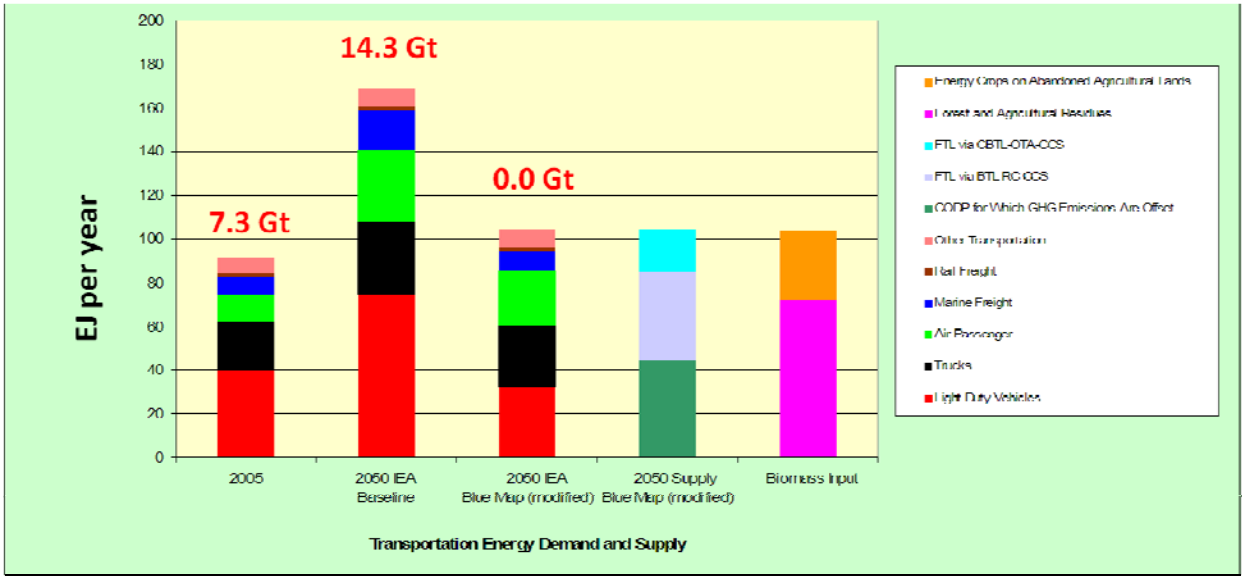

Figure 12.1 Energy and GHG emissions for coal/biomass thought experiment and for IEA 2050 Base-line (Business as Usual) scenario. Numbers at tops of bars are total GHG emissions in Gt CO_{2eq} per year.

the Baseline Projection in order to reduce global emissions by 50% relative to emissions in 2005.

While transportation demand in 2050 is essentially that in the Blue Map Scenario, we modify the Blue Map scenario using the assumption that in the period to 2050 no plug-in hybrid vehicles, no all-electric vehicles, and no H_2 fuel cell vehicles are included in the light-duty vehicle (LDV) mix. This is in contrast to the actual Blue Map Scenario, which assumes a high penetration of these technologies in the mix by mid-century.[8] Obviously, this exclusion is not a realistic assumption, because these technologies are being heavily promoted by governments. The main reason for the exclusion is to bring to the attention of policymakers that, as shown in this KM, deep reductions can plausibly be realized at attractive production costs with essentially no costly changes in fuel infrastructures via pursuit of CCS for coal and biomass and with evolutionary rather than revolutionary changes in automotive engine technologies. In particular, energy-efficient LDVs[9] (e.g., advanced gasoline and diesel hybrid electric vehicles) are emphasized in our Modified Blue Map Scenario. Our hope is that this modified Blue Map scenario will inspire policymakers to take a more balanced approach to decarbonizing the

[8] In 2050 the LDV fleet in the IEA Blue Map Scenario (IEA, 2009b) is made up of 37% plug-in hybrids, 21% all-electric vehicles, and 25% H2 hybrid fuel cell vehicles.

[9] In the (IEA, 2009) scenarios average fuel economies for new LDVs in 2050 are 5.9 liters of gasoline equivalent per 100 km (l_{ge}/100 km) or 40 miles per gallon of gasoline equivalent (mpg_{ge}) for the Baseline Scenario and 2.9 l_{ge}/100 km (81 mpg_{ge}) for the Blue Map Scenario. The average fuel economy assumed for the entire LDV stock in 2050 in the Modified Blue Map Scenario is 2.9 l_{ge}/100 km (62 mpg_{ge}), which is consistent with the IEA assumptions for the average fuel economy for new LDVs in the Actual Blue Map Scenario. There are reasonable prospects that this average fuel economy for the LDV stock could be realized without use of plug-in hybrids or fuel cell vehicles. (Kromer and Heywood, 2007) have estimated that by 2030 a mid-sized conventional hybrid-electric car (essentially a 2030 version of a Prius) could have a fuel economy of 3.1 l_{ge}/100 km (76 mpg_{ge}).

transportation sector and create policies that enable the low carbon transportation technology options that have been the focus of KM 12 to compete alongside the technologies that are intensely promoted in current policies.

The resulting liquid fuel demand and supply for global transportation under the Modified Blue Map Scenario are shown as the 3rd and 4th bars of Figure 12.1. Total net GHG emissions are zero for global transportation in 2050 under the conditions of the Global C/B TE. The liquid fuel supply would be made up of 19% FTL via CBTL-OTA-CCS, 38% FTL via BTL-RC-CCS, and 43% crude oil–derived products. The level of crude oil-derived products used in transportation is 51% of the amount of crude oil derived products used for transportation worldwide in 2005. The projected GHG emissions are zero despite the large share of crude oil-derived products in the mix because it is assumed for the Global C/B TE that the negative emissions from BTL-RC-CCS systems are used to offset GHG emissions from both crude oil-derived products and CBTL-OT-CCS plants.

In 2050 coal use for the Modified Blue Map (with the Global C/B TE) is 1.15 X global coal use in 2005, compared to 0.78 X for the IEA Blue Map Scenario and 3.04 X for the IEA Baseline Scenario.

Under the conditions of the Global C/B TE, CO_2 storage would be carried out in 2050 at rates of 3.7 billion tonnes per year for CBTL-OTA-CCS plants and 4.8 billion tonnes per year for BTL-RC-CCS plants. This finding highlights the importance of ascertaining the extent to which there are good geological CO_2 storage opportunities in biomass-rich but coal-poor regions—where consideration of CCS as a carbon mitigation option has probably not been given much thought.

Is it plausible that ~ 10,000 BTL-RC-CCS plants[10] might be up and running by 2050 (each processing 0.5 million tonnes of biomass annually)? If one imagines starting with 20 such plants by 2030 the annual average growth rate in plant deployment, 2030-2050, would have to be 37% per year. This extraordinarily high growth rate would not take place without supportive public policy, but it is not inconceivable. In its heyday, nuclear power grew worldwide at a sustained average growth rate of 37% per year, 1957-1977.

Much of this growth would take place in now impoverished developing countries, where this technology would represent a major opportunity for industrial growth. But many such countries currently have neither the needed physical infrastructures (roads, railroads, pipelines, port facilities for managing exports, etc.) nor the human capacity to manage such industrial growth. But the technology is not likely to be cost competitive until ~ 2030 so there is a strategic opportunity to build those needed capacities in the interim if the global community comes to think that there is a pressing need for this industry.

<u>A final thought relating to the Global C/B TE</u>: If the goal for decarbonizing global transportation were to reduce by 2050 GHG emissions for transportation worldwide not to zero but rather to half the 2005 level (in line with current long-term policy goals for carbon mitigation), the global biomass requirements for 2050 drop to a level that is only 38% higher than global biomass use in 2005—so that considerable biomass would be available for purposes other than to satisfy Global C/B TE needs. Moreover, crude oil-derived products (in an amount equivalent to 69% of the level for transportation in 2005) would account for 60% of total transportation energy in 2050.

[10] Each of which provides 2,200 barrels per day of gasoline equivalent FTL + 14 MW_e of electricity and requires an investment of $420 million.

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