Carbon Management Technology Conference 2017, Houston, TX

Toward Negative Emissions on Electric Grids With High Penetrations of Intermittent Renewables

Robert H. Williams, Senior Research Scientist Emeritus
Andlinger Center for Energy and the Environment
Princeton University
18 July 2017

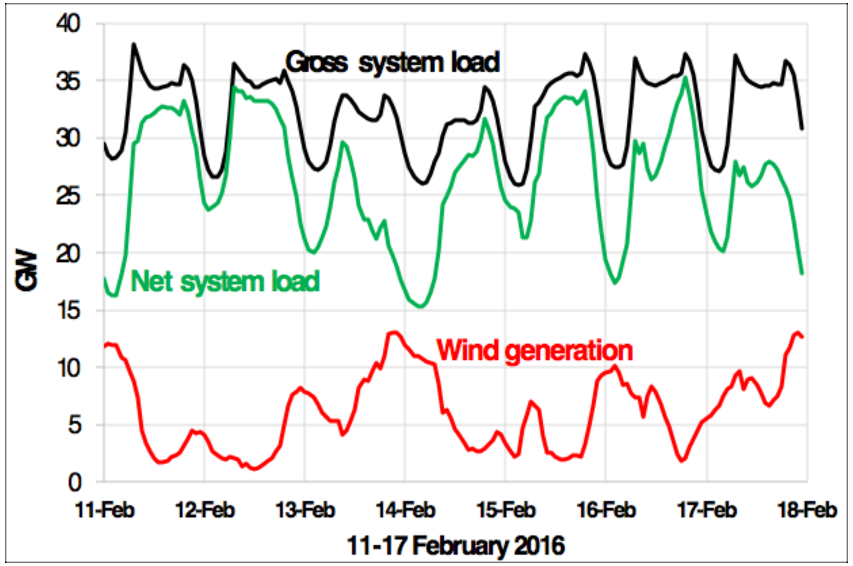
BECCS as Carbon Mitigation Option

- The 2015 Paris Climate Accord, since ratified by 153 countries, seeks to limit the rise in global temperature to 2 ^oC [**2DS future**] and 1.5 ^oC if possible.
- According to the IPCC's 5AR:
  - "Many models cannot reach concentrations of about 450 ppm CO_{2e} by 2100 [roughly equivalent to a 2DS future] in the absence of CCS," and
  - "Many models could not limit ***likely* warming to below 2°C** if bioenergy, CCS, and their combination (BECCS) are limited *(high confidence).*"
- In *Energy Technology Perspectives 2017* the IEA charted a possible path for global energy to 2060 consistent with limiting global warming to 1.75 ^oC—a path that gives prominence to BECCS—e.g., photosynthetic CO_2 storage in geological media at a rate of ~ 300 Mt/y by 2030 (15% of total global CCS) and ~ 4900 Mt/y by 2060 (45% of total global CCS).
- But progress has been slow in advancing BECCS technologies.
- Proposal to accelerate BECCS development:
  - Launch BECCS in market via coprocessing coal and biomass:
    - Benefits to BECCS: lower average feedstock costs/economies of scale compared to "pure" BECCS;
    - Benefit to coal: path whereby coal in US might be better able to compete with low-cost natural gas under a carbon policy…by exploiting economic benefit of negative emissions.
  - Carry out coal/biomass coprocessing with CCS with aim of decarbonizing balancing capacity on electric grids with high penetrations of intermittent renewables—a high priority in quest for a low carbon energy future.

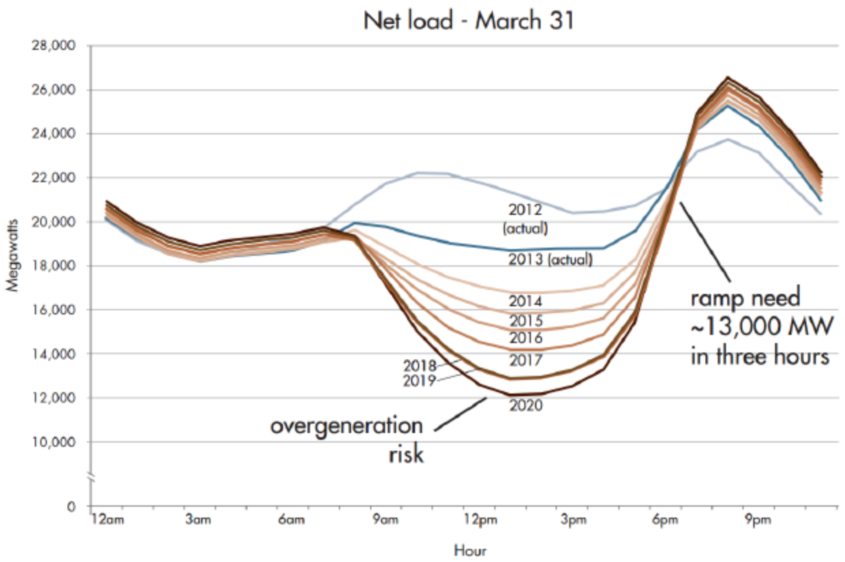
Timeliness of BECCS Market Launch via Coal/Biomass Coprocessing

- There is a reasonable chance that in 2017 **S.1460** (*Energy and Natural Resources Act of 2017*) will be enacted—passed Senate, 20 April 2016, but needs to be reconciled with House version.
- *Inter alia*, **S.1460** authorizes FE to spend $22 million/year for 5 years (2018-2022) for support of FEED studies for net-negative CO_2 emissions projects. The term 'net-negative carbon dioxide emissions project' means a project employing technologies for thermochemical co-conversion of coal and biomass with CCS that:
    - The Secretary of Energy determines can provide electricity, fuels, or chemicals with net-negative carbon dioxide emissions from production and consumption of the end products, while removing atmospheric CO_2;
    - Will proceed initially through a large-scale pilot project for which front-end engineering will be performed for bituminous, subbituminous, and lignite coals; and
    - Through which each use of coal will be combined with the use of a regionally indigenous form of biomass energy, provided on a renewable basis, that is sufficient in quantity to allow for net-negative emissions of carbon dioxide (in combination with a carbon capture system), while avoiding impacts on food production activities.
- Co-sponsored by Senators Murkowski (R-AK) and Cantwell (D-WA), **S.1460** has broad bipartisan support.
- The 'net-negative CO_2 emissions project' provision of **S.1460** was developed by Senator Manchin (D-WV).
- The 'net-negative carbon dioxide emissions project' provision is consistent with President Trump's promise to find ways to advance coal.
- The seminal Sanchez and Kammen (2016) article highlights the strategic importance of BECCS market launch via coal/biomass coprocessing.

Toward Reliable Grid Power with High Penetrations of Intermittent Renewable Electricity (IRE)



7 days of wind power and electric load for ERCOT grid (Texas)

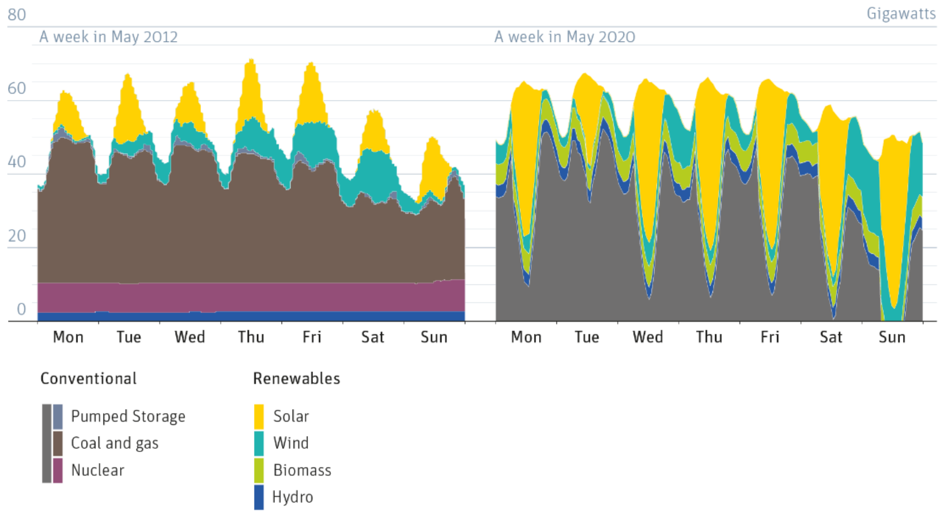


"Duck Curve" for CAISO grid (California)

- Ongoing technological revolution in IRE technology, with attendant remarkable cost reductions, is likely to continue for decades.
- Fast-ramping balancing capacity (BC) (some combination of backup capacity and storage capacity) is needed to ensure reliable grid power at high IRE grid penetrations.
- BC is often provided in US today by mix of natural gas (NG)-fired gas turbine combined cycle (GTCC) and combustion turbine (CT) units, but…

Toward CCS for Balancing Capacity at High IRE Penetrations

- Paris climate goals ➔ BC must eventually (post-2030) be decarbonized—e.g., via CO_2 capture and sequestration (CCS)—with CO_2 storage via EOR, in deep saline formations, etc.
- "Early mover" CCS projects should be deployed during next decade to gain experience and get underway technology cost buydown (TCB) process ("learning by doing").
- CCS energy systems are capital intensive ➔ require continuous (baseload) operation.
- At high IRE penetrations, BC plants must be operated at low capacity factors (CFs): 30% to 50% (not baseload!).
- At even relatively modest IRE grid penetrations, roles for baseload power will be limited as illustrated by the situation in Germany:



These curves show the Germany electricity load for 1 week in May in 2012 (left, when IRE accounted for 13% of electricity generation) and for 1 week in May in 2020 (right, when IRE is expected to account for 29% of electricity generation). **It is striking that with < 30% IRE in 2020 there is "no room" on German grid for baseload power.**

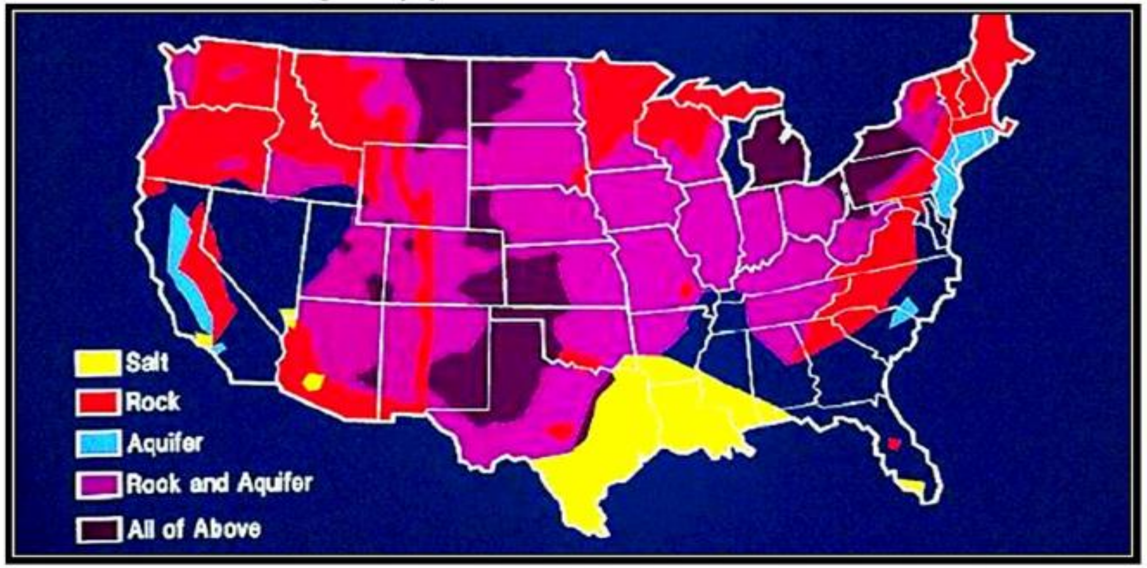
- A hydrogen balancing capacity (H_2-BC) approach for addressing this challenge is discussed.

Firming Up Electric Grids at High IRE Penetrations with H_2-Balancing Capacity

- Three elements of a H_2-BC system [see, e.g., Davison (2009), ETI (2015)]:
  - H_2 is produced in baseload (~ 90% CF) plants with CCS from natural gas (NG), coal, biomass, or coal/biomass or NG/biomass;
  - H_2 is consumed in fast-ramping BC units [e.g., CT, GTCC, proton exchange membrane (PEM) fuel cells, or compressed air energy storage (CAES) units] that operate at low CFs;
  - H_2 is stored in buffer underground storage systems to enable decoupling baseload H_2 production from highly variable H_2 consumption by BC units.
- The concept "works" because underground H_2 storage part of system expected to be inexpensive [see, e.g., Davison (2009), ETI (2015)].
- Present focus:
  - H_2 with CCS via cogasification of coal + torrefied corn stover—a promising approach for enabling coal to compete with natural gas in a carbon-constrained world based on near-term technologies
    - Making H_2 from coal is commercial technology—hundreds of Chinese plants that make fertilizer from coal;
    - Corn stover is an abundant biomass supply that can be exploited in near term;
    - Torrefaction process for corn stover is ready to be demonstrated at commercial scale;
    - Cogasification of coal/torrefied biomass is technically feasible and ready for commercial-scale demonstration.
  - H_2 so produced can be used in CT, GTCC, PEM fuel cells or CAES units.
  - It is assumed (pessimistically) that captured CO_2 is stored in deep saline formations.
  - In near term, underground buffer storage of H_2 is feasible only in salt caverns.

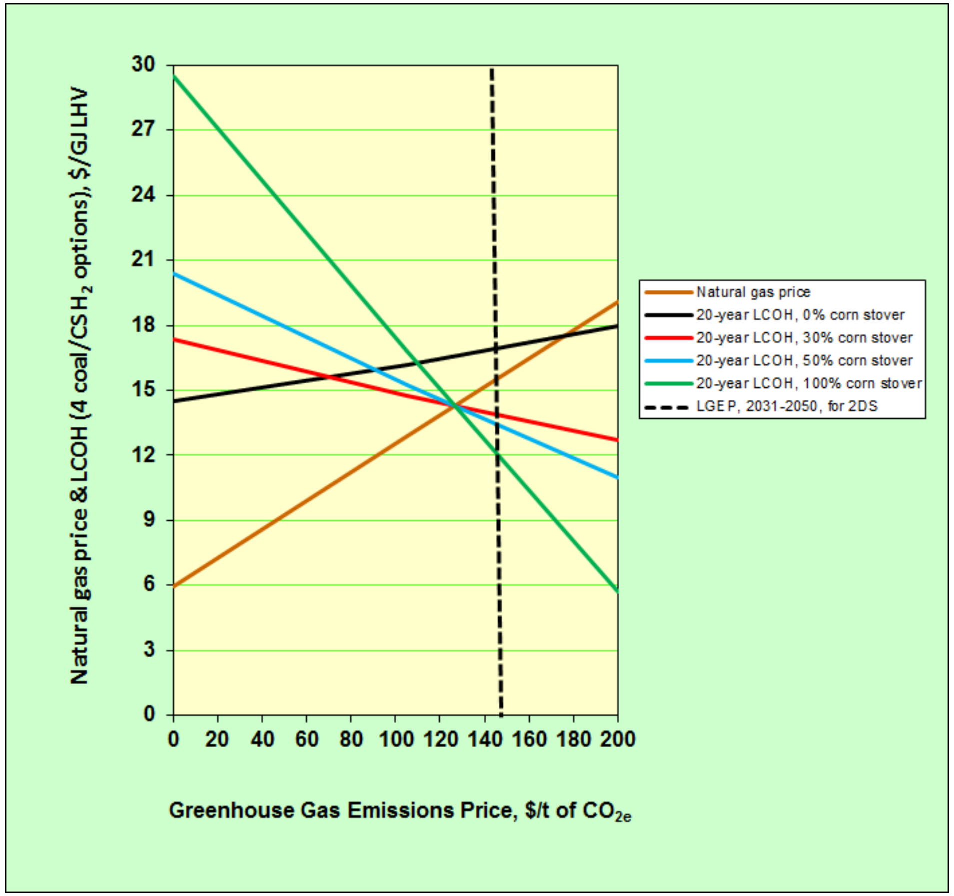
Underground Storage of H_2

	Clemens (USA)	Moss Bluff (USA)	Teesside (UK)
Geology	Domal salt	Domal salt	Bedded salt
Operator	Conoco Phillips	Praxair	Sabic Petroleum
Stored fluid	Hydrogen	Hydrogen	Hydrogen
Commissioned	1983	2007	~1972
Volume [m³]	580,000	566,000	3 x 70,000
Reference depth [m]	930	> 822	350
Pressure range [bar]	70 - 135	55 - 152	~ 45
Possible working gas capacity H_2 Mio [kg]	2.56	3.72	0.83



- Since 1972 H_2 has been stored in 3 caverns in bedded salt in UK (at Teeside).
- H_2 is also being stored in 2 caverns in salt domes on Texas Gulf Coast.
- Because of limited geographical availability of these salt formations in the US, underground storage of H_2 in porous media (aquifers and depleted HC fields) and rock caverns are also desirable; with these additional options the H_2-BC strategy could be pursued in most parts of US.
- In recent years, H2STORE and HyINTEGER programs in Germany have supported R&D on H_2 storage in porous media (Pudlo et al., 2013; 2016; Pfeiffer et al., 2016; Pfeiffer et al., 2017; Energy Storage Funding Initiative, 2017).
- Little US R&D on H_2 storage in porous media has been carried out recently, although this was to have become a key targeted R&D activity under the 2016 interagency, EERE-led *H_2 at Scale Initiative*, which envisioned major roles for H_2 as necessary to realize the Obama Administration's goal of deep reductions in US GHG emissions by midcentury.

Levelized cost of H_2 vs GHG Emissions Price for Alternative Options for Making H_2 w/CCS (via Co-gasification of Coal + Torrefied Corn Stover)—with Comparisons to NG Price

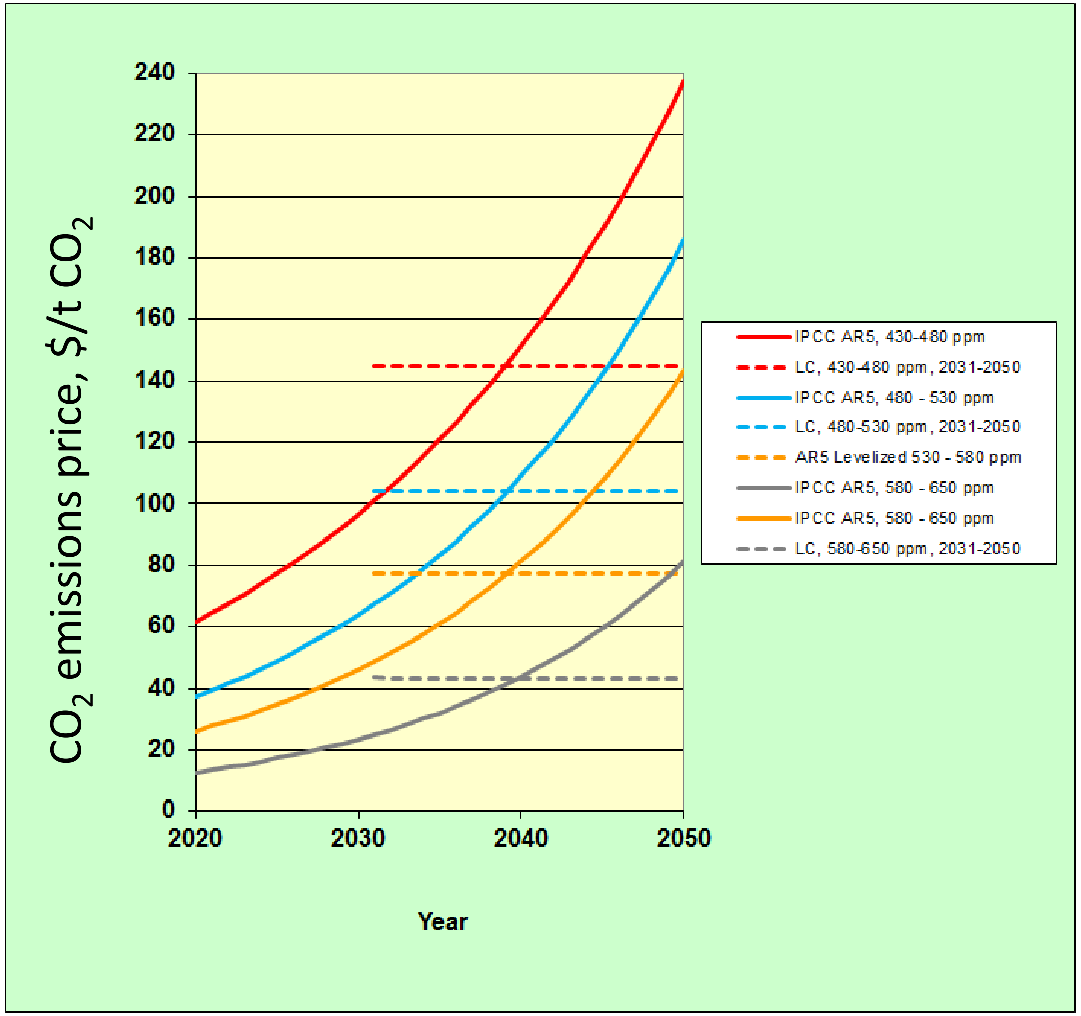


- Preliminary cost estimates neglecting H_2 storage costs (NOAK plants); O_2-blown quench gasifier; 93% CO_2 capture, CO_2 storage in deep saline formations (see Appendix for details).
- All options using corn stover (CS) consume 1 x 10^6 dry t/y.

	Prices in absence of GEP, \$/GJ HHV
Natural gas	5.4
Coal	2.1
Corn stover	3.9
Torrefied corn stover	6.9
For H2 from:	**GHG emissions** (relative to NG emissions)
100% Coal	**+ 0.18**
70% coal + 30% corn stover	**- 0.31**
50% coal + 50% corn stover	**- 0.68**
100% corn stover	**- 1.8**

- For negative emission options, LCOH falls with GHG emissions price.
- For **100% corn stover:** H_2 capacity 0.3X that for **30% corn stover**; average feedstock cost 2X more.
- LCOHs for all CS options < NG price (including emissions charge) for GHG emissions prices > \$137/t CO_{2e}.
- Post 2030, this GHG emissions price < CO_2 price consistent with realization of 2DS for global energy future.

CO_2 Price Trajectories (solid curves) for Alternative Atmospheric CO_2 Stabilization Scenarios & Corresponding Levelized CO_2 Prices, 2031-2050 (dashed curves)



- At left are CO_2 emission price trajectories (solid curves) consistent with 4 alternative scenarios for stabilizing atmospheric CO_2 concentrations for these emissions strategies, according to IPCC's AR5.
- Solid **red curve** roughly consistent with limiting global warming to 2 °C (2DS global energy future).
- Dashed **red curve** = levelized cost of CO_2 emissions, 2031-2050, = $145/t CO_2 (dashed vertical **black curve** on previous graph).

Policy Recommendations for Advancng the Coal/Biomass H_2-BC Concept

- DOE should support detailed pre-feasibility/feasibility studies of coal/biomass H_2-BC concept for providing reliable negative-emissions electricity on electric grids with high penetrations of IRE—as well as R&D on key component technologies.
    - If those studies sustain the preliminary findings presented here that the coal/biomass H_2-BC concept is promising under a strong carbon mitigation policy, and
    - If the final (reconciled) version of **S.1460** contains the 'net-negative CO_2 emissions project' provision.

  then DOE should consider supporting, via the **S.1460** authorization, at least 1 FEED study for advancing the concept. This strategy ought to be embraced by the Trump Administration, because:
    - Pres. Trump is committed to advancing coal's role in the US energy economy, and
    - A U.S. program focused on net-negative CO_2 emissions technology development would be seen as "proof positive" of Sec. Perry's assertion that departing the Paris Climate Accord does not mean the U.S. will abandon its technology leadership in vital areas that can contribute solutions for mitigation.
- In parallel, DOE should support systems analyses exploring natural gas-based balancing capacity options for providing reliable zero or negative-emissions electricity on electric grids with high penetrations of IRE—one aim of which would be a better understanding of the prospective competition between coal and natural gas in providing low, zero or negative emitting balancing capacity.
- Finally, high priority should be given to finding ways to fix electricity markets that have been "broken" by the IRE revolution (Larson et al., 2017)—e.g., these markets do not provide investors adequate incentives to build new capacity needed to ensure a reliable grid electricity supply even though that capacity will be idle most of the time at high grid penetrations of IRE.

Is a Viable Long Term Future for Coal Possible in US Power Market?

- Abandoning the Paris Climate Accord and halting incentives for renewables will do little to create a Coal Renaissance in the US power market because of fierce competition from abundant gas at prospective natural gas prices.
- Substantial US power market roles for coal in the presence of an eventual strong US carbon mitigation policy (likely in ~ 4-8 years) are not possible without CCS.
- But high grid penetrations of IRE with attendant greatly reduced demand for baseload grid power make CCS very challenging economically for coal CCS technologies, because these very capital-intensive systems must be operated at high (baseload) capacity factors to be competitive.
- This capital intensity challenge can be addressed effectively by pursuing CCS via the H_2-BC concept—which makes it possible to carry out CCS with a system part (H_2 production) that operates at a high (90%) capacity factor while the much less capital-intensive part of the system (flexible balancing capacity) operates at low capacity factors.
- Deploying coal-based H_2-BC systems in the US is not likely to be sufficient to enable coal to compete with natural gas because unrealistically high GHG emission prices would be required to realize breakeven between coal-derived H_2 and natural gas.
- However, there are reasonably good prospects that, for IRE-intensive electric grids, coal/biomass H_2-BC systems characterized by strong negative GHG emission rates would be able to compete as balancing capacity against natural gas-fired GTCC and CT options at GHG emissions prices consistent with a 2DS global energy future.
- Ascertaining how successful coal/biomass H_2-BC systems might be in competing against advanced low, zero, or negative emitting natural gas balancing capacity options (e.g., natural gas fired Allam cycles, natural gas-fired H_2-BC systems, and natural gas/biomass-fired H_2-BC systems) on IRE-intensive grids should be a priority focus of future energy systems studies.

References

Davison, John, “Electricity systems with near-zero emissions of CO_2 based on wind energy and coal gasification with CCS and hydrogen storage,” *International Journal of Greenhouse Gas Control*, **3:** 683–692, 2009.

Energy Storage Funding Initiative, “HyINTEGER: Long-term underground storage of hydrogen,” German Federal Ministry for Economic Affairs and Energy and Federal Ministry of Education and Research, 18 April 2017. (Website accessed 11 May 2017: http://forschung-energiespeicher.info/en/projektschau/gesamtliste/projekt-einzelansicht/127/Wasserstoff_langfristig_unterirdisch_speichern/.)

ETI (Energy Technologies Institute), *The Role of Hydrogen Storage in a Clean Responsive Power System*, Holywell Building, Holywell Way, Loughborough LE11 3UZ, United Kingdom, www.eti.co.uk, 2015.

Kreutz, Tom, Eric Larson, and Bob Williams, “Understanding Challenges with Intermittent Renewable Electricity Expansion,” contribution of the Energy Systems Analysis Group (ESAG), Andlinger Center for Energy and the Environment, to the *2017 Annual Report of the Carbon Mitigation Initiative of Princeton University*, April 2017, http://cmi.princeton.edu/annual_reports/2016/integration/index.php#cio_2

Pfeiffer, W.T., S.A., Hagrey, D. Köhn, W. Rabbel, and S. Bauer, “Porous media hydrogen storage at a synthetic, heterogeneous field site: numerical simulation of storage operation and geophysical monitoring,” *Environmental Earth Sciences*, 75(16): 1177, 2016. doi:10.1007/s12665-016-5958-x.

Pfeiffer, W.T., C. Beyer, and S. Bauer. (2017). Hydrogen storage in a heterogeneous sandstone formation: dimensioning and induced hydraulic effects. *Petroleum Geoscience*, petgeo2016-2050.

Pudlo, D., L. Ganzer, S. Henkel, M. Kuhn, A. Liebscher, M. De Lucia, M. Panfilov, P. Pilz, V. Reitenback, D. Albrecht, H. Wurdemann, and R. Gaupp, “The H2STORE Project: Hydrogen Underground Storage – A Feasible Way in Storing Electrical Power in Geological Media?,” in *Clean Energy Systems in the Subsurface: Production, Storage, and Conversion*, M.Z. Hou, *et al*. (eds), Springer Verlag, Berlin, 2013, pp. 395-412.

Sanchez, D.L., and D.M. Kammen, “A commercialization strategy for carbon-negative energy,” *Nature-Energy*, 11 January 2016 https://www.nature.com/articles/nenergy20152

Appendix: Documentation for Calculations Presented in Slide # 8

The final version of this appendix will have a detailed discussion of assumptions leading to the construction of the cost calculations presented in Slide 8. At present, only relevant citations are indicated.

Citations for Appendix

Chiesa, P., S. Consonni, T. Kreutz, and R. Williams, "Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology. Part A: Performance and Cost," *International Journal of Hydrogen Energy*, **20**: 747-767, 2005.

EIA (Energy Information Administration), *Annual Energy Outlook 2017*, January 2017.

Kreutz. T., R. Williams, S. Consonni, and P. Chiesa, "Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology. Part B: Economic analysis," *International Journal of Hydrogen Energy*, **20**: 769-784, 2005.

Larson, E., G. Fiorese, G. Liu, R. Williams, T. Kreutz, and S. Consonni, "Co-production of synfuels and electricity from coal + biomass with zero net greenhouse gas emissions: an Illinois case study," *Energy and Environmental Science*, **3**: 28-42, 2010.

NETL (National Energy Technology Laboratory), *Assessment of H_2 Production with CO_2 Capture*, Volume 1: Baseline State-of-the-Art Plants, DOE/NETL-2010/1434, 30 August 2010.

NETL (National Energy Technology Laboratory), *Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity*, Revision 3, DOE/NETL-2015-1723, 6 July 2015.

Svanberg, M., I. Ollafson, J. Floden, and A. Nordin, "Analyzing Biomass Torrefaction Supply Chain Costs," *Biosource Technology*, **142**: 287-296. 2013.