Coal + Biomass → Liquids + Electricity (with CCS)

MATTHEW L. AITKEN
ORISE Research Fellow
U.S. Environmental Protection Agency

Objective of this presentation

- To examine the potential role in the U.S. energy system of a technology that converts coal and biomass inputs to Fischer-Tropsch liquid fuels and electricity

Outline

- Introduction/Background
  - coal and biomass to liquids and electricity (CBtLE)
  - carbon capture and storage (CCS)
  - levelized cost of energy (LCOE)
  - MARKet ALlocation (MARKAL) model
- Methods
- Results
  - CBtLE sensitivity to:
    - carbon policy
    - oil prices
    - CCS costs
  - Regional variations in CBtLE development
- Conclusion/Future work

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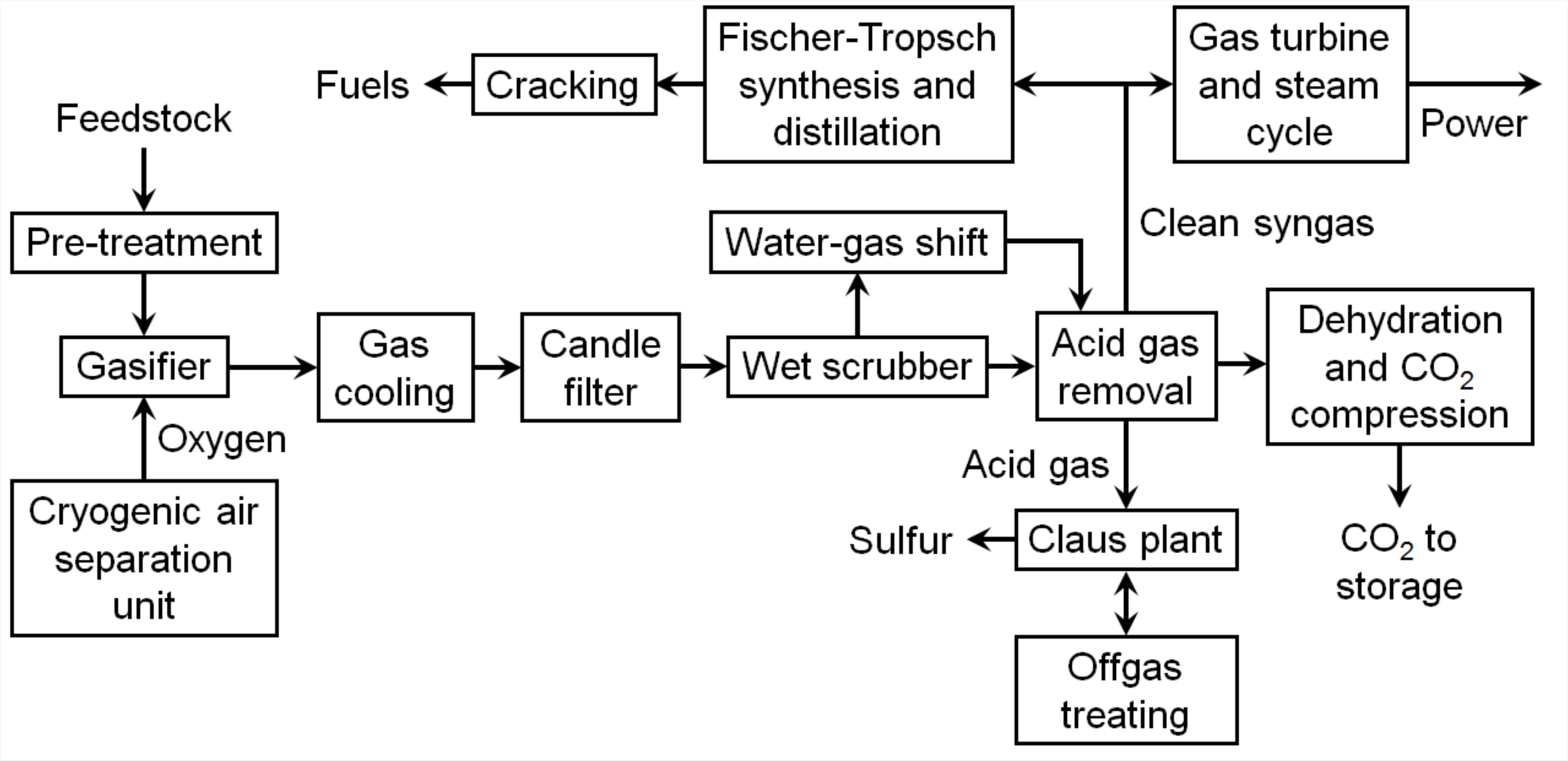
Introduction

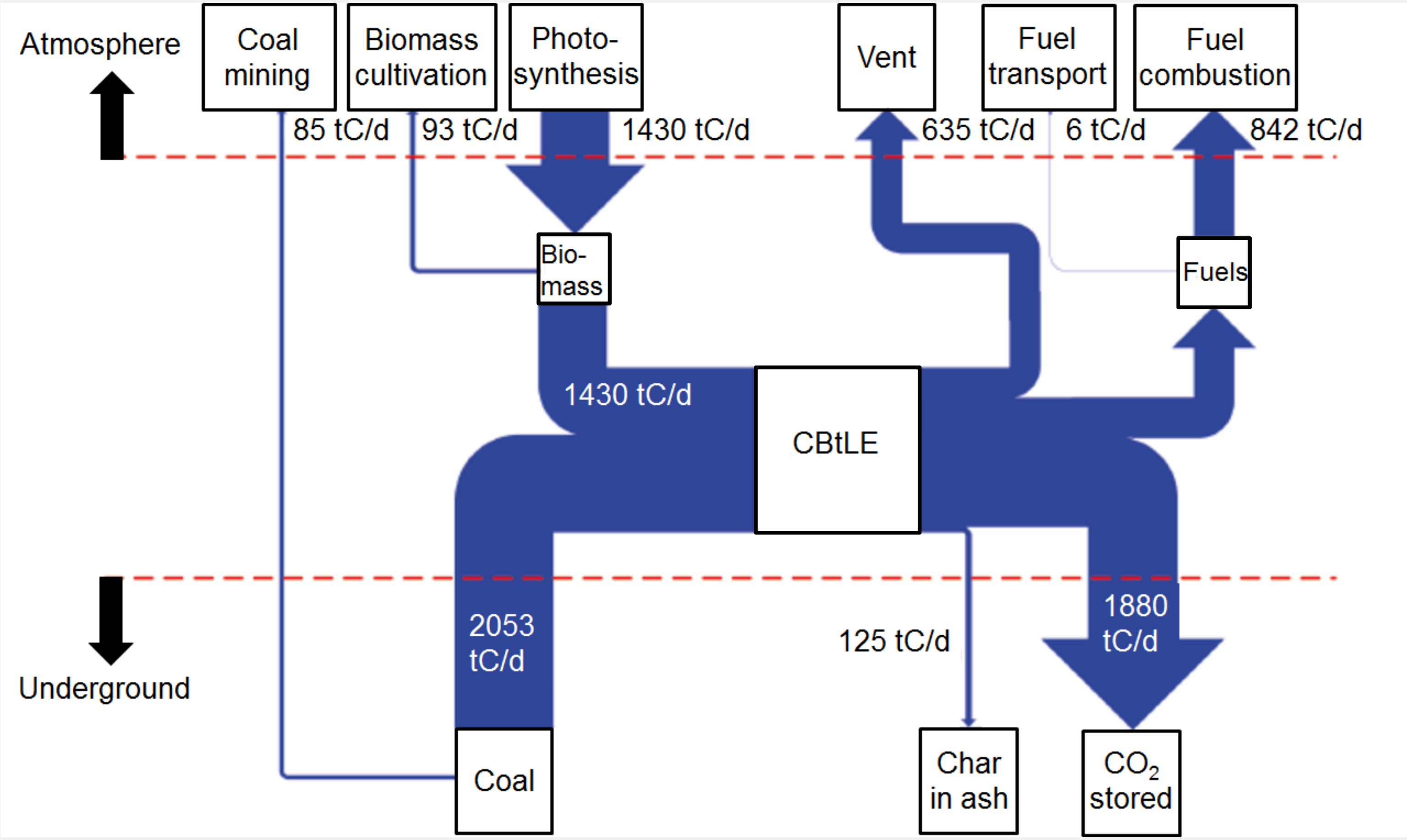
- Must decarbonize the global energy system at an unprecedented scale to avoid the worst consequences of climate change
  - in both the electricity and transportation sectors
- But there is considerable uncertainty in the evolution of:
  - fuel and materials costs
  - technological learning
  - environmental regulations
- Thus, it would be prudent to investigate and develop a diverse portfolio of low-carbon energy technologies
  - particularly those that can accept multiple inputs and produce multiple outputs

CBtLE w/ CCS process overview



*adapted from Knoope et al. *Int. J. Greenh. Gas Con.* **16**, 287–310 (2013)

Carbon flow example for a 750 MW CBtLE plant



*adapted from Liu et al. *Energy Fuels* **25**, 415–437 (2011)

History of Fischer-Tropsch fuels

- **1930** Patent published for Fischer-Tropsch process
- **1936** Fischer-Tropsch first commercialized in Germany
  - used by the Nazis in World War II
    - accounted for ~10% of German wartime fuel production
- **1952** Fischer-Tropsch first commercialized in South Africa
  - South Africa has large coal reserves but little oil
  - Fischer-Tropsch now produces most of the country's diesel
- **1980s** Low oil prices and F-T project cost overruns
  - killed postwar support for R&D and commercialization of synthetic fuels in U.S.

Recent news for coal/biomass gasification

- **2009** U.S. Air Force coal-to-liquids initiative ended
- **2011** Choren Industries declared bankruptcy
  - biomass-to-liquids producer in Germany
- **2011** Baard Energy coal-to-liquids plant in Ohio cancelled
- **2014** Syntroleum delisted from NASDAQ
  - coal-to-liquids producer in Tulsa, OK
- **2014** China plans to build 50 coal gasification plants (some with CCS) in remote areas to reduce urban air pollution
- **2015** Handful of biomass-to-liquids demonstration projects in planning stage in Europe
- **2015** Coal/biomass-to-liquids facility planned in Alaska

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Current status of carbon capture and sequestration

- Coal unit at Boundary Dam Power Station in Saskatchewan retrofit to include CCS
  - reopened in October 2014
  - 90% reduction in CO_2 emissions
  - CO_2 used for enhanced oil recovery
- Kemper County energy facility (IGCC + CCS)
  - $6 billion | 600 MW | 65% CO_2 capture
  - scheduled to open in 2016, two years behind schedule
- DOE has suspended funding for FutureGen 2.0
- Hydrogen Energy California coal plant and Texas Clean Energy Project unlikely to move forward
  - ARRA funding in jeopardy for missing construction deadlines

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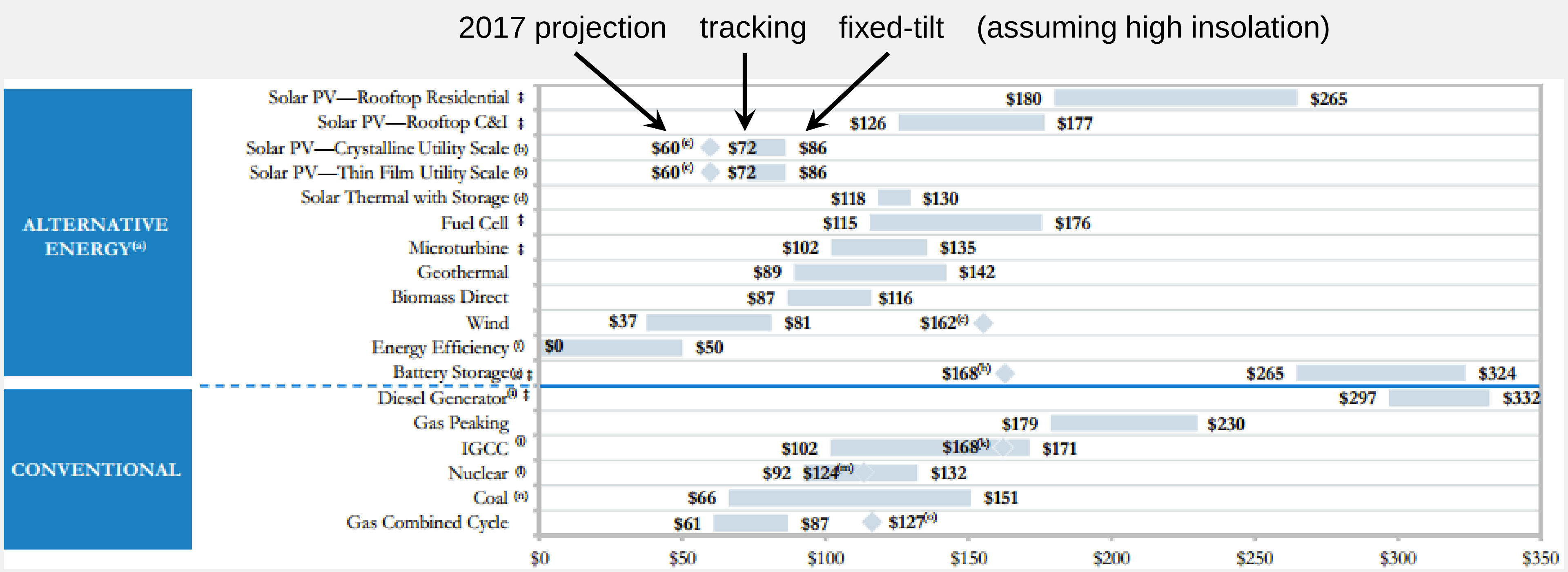
Levelized cost of energy (LCOE)

- $\mathrm{LCOE} = \frac{\sum(\mathrm{capital} + \mathrm{O\&M} + \mathrm{fuel})\ \mathrm{costs}}{\sum \mathrm{energy\ generation}}$
- Convenient summary measure of overall competitiveness
- But fails to account for:
  - existing resource mix & projected utilization rate
  - capacity value
  - raw material & land constraints
  - pollutant emission rates

Unsubsidized LCOE estimates by Lazard [in $/MWh]

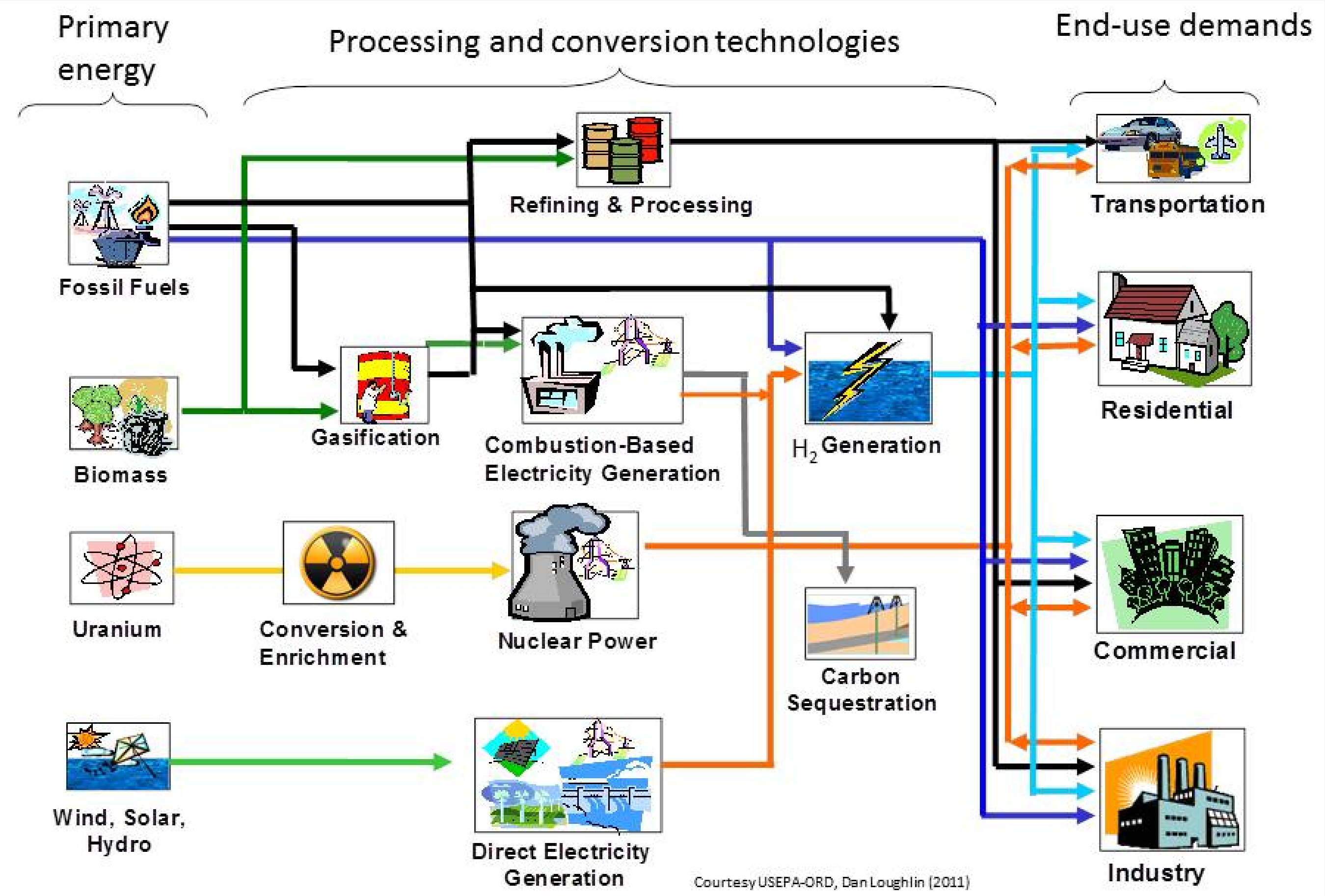


*adapted from Lazard's Levelized Cost of Energy Analysis – Version 8.0

MARKet ALlocation (MARKAL) energy system model

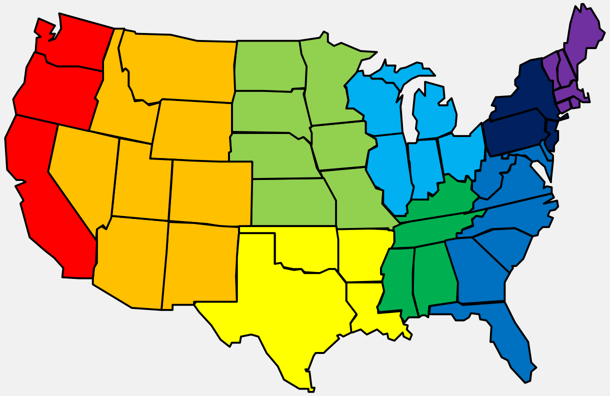
- More comprehensive tool than LCOE
- Linear programming model
- Solves for optimal energy system evolution
  - based on net present value (NPV)
- Allows for imposition of resource/policy constraints
- Can be used to conduct nested sensitivity analysis
  - which combinations of conditions/assumptions drive certain technological pathways?

MARKAL energy system model



EPA MARKAL databases

- Represent economic/environmental characteristics of U.S. energy system
- (1) EPANMD national database
  – no longer updated as of 2010
- (2) EPAUS9r regional database
  – calibrated to projections in EIA's Annual Energy Outlook 2014
  – partitions the country according to 9 U.S. Census Divisions



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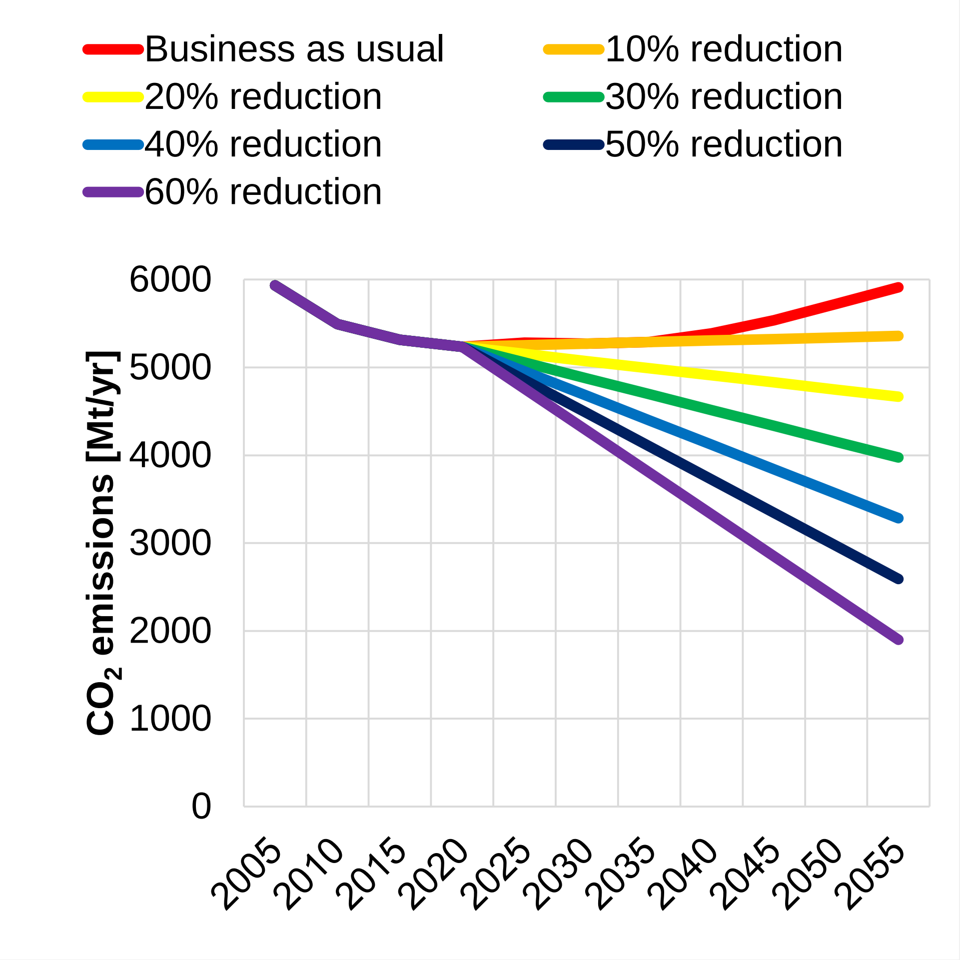
CBtLE implementation in MARKAL

- Statistics from 18 sources in the literature averaged to characterize a representative CBtLE plant in MARKAL

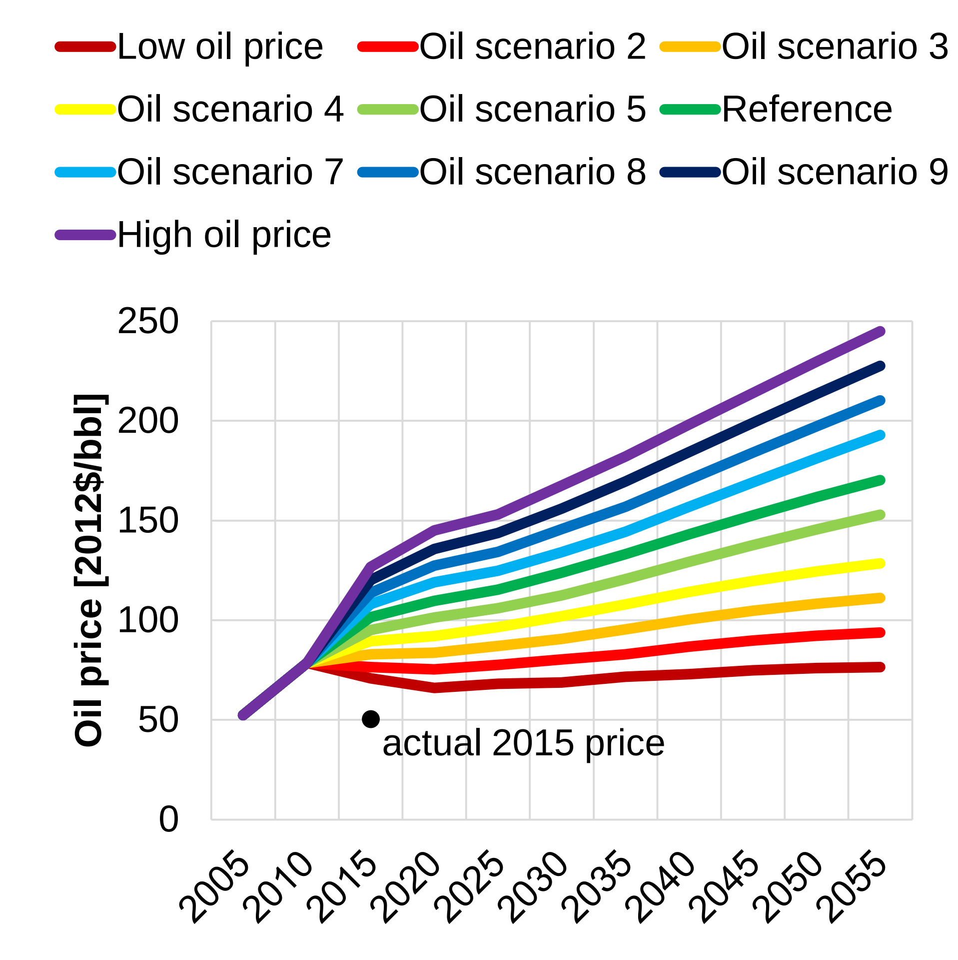
Plant life	25 years
Capacity factor	90%
Efficiency	53%
Input fractions (energy basis)	70% coal | 30% biomass
Output fractions (energy basis)	58% diesel | 22% gasoline | 20% electricity
Capital cost	$2023/kW
Fixed O&M cost	$125/kW
Variable O&M cost	$13/MWh for coal | $23/MWh for biomass
CO_2 emitted	0.07 tonne/MWh
CO_2 stored	0.39 tonne/MWh

Carbon policy scenarios

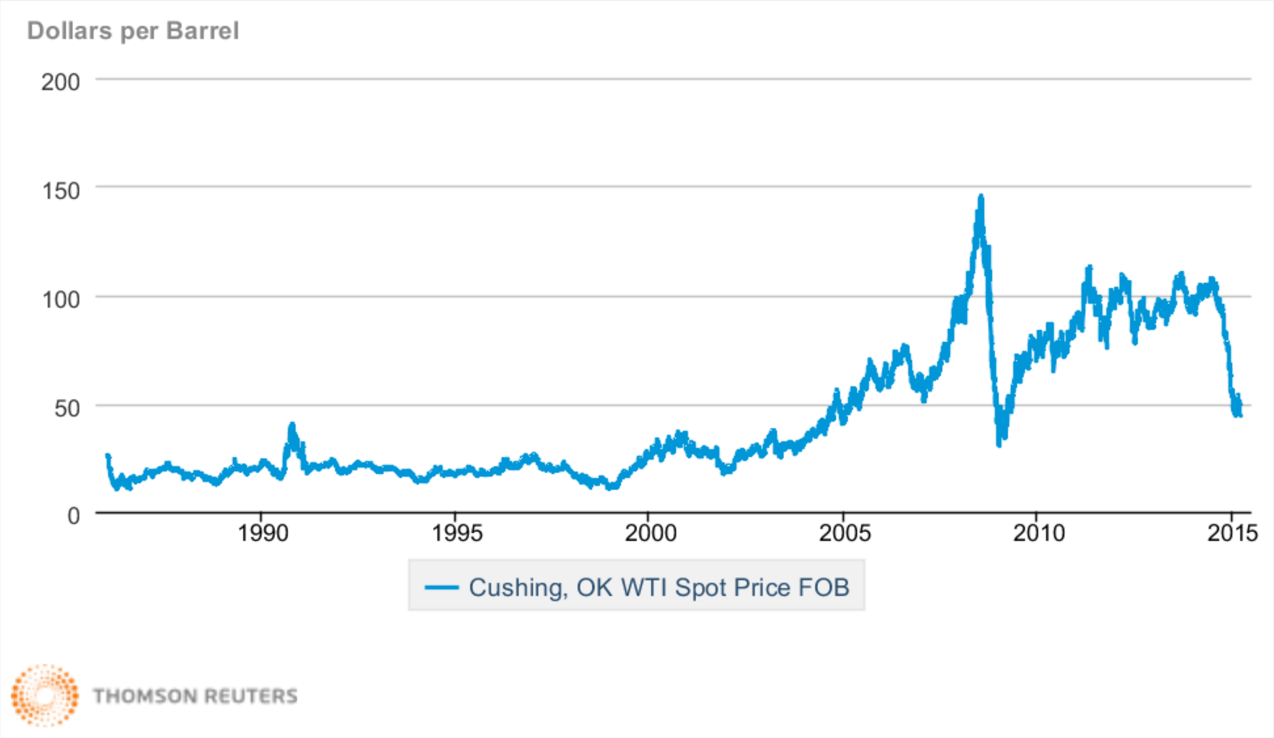


*percent reduction denotes 2050 emission level relative to 2005

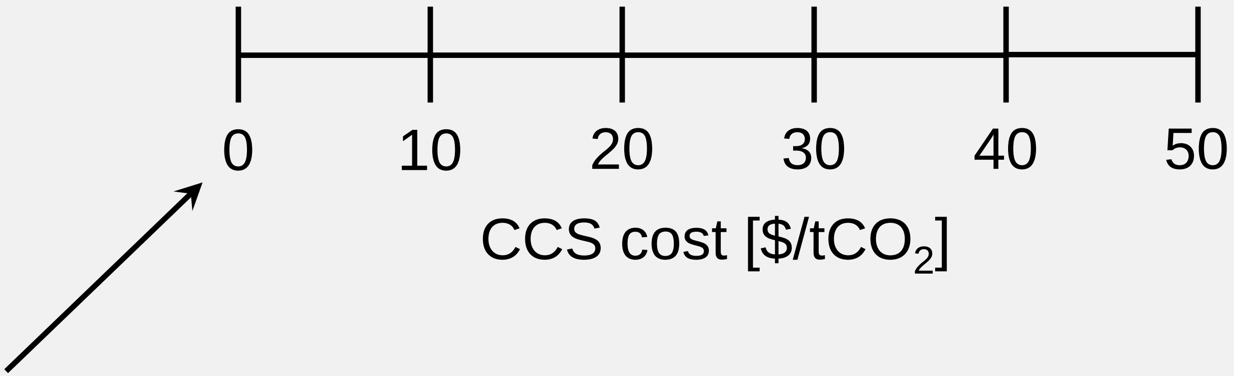
Oil price scenarios



Useful to study oil price sensitivity because of historic volatility



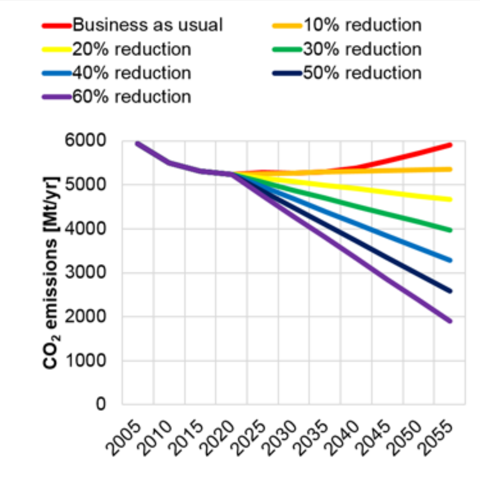
CCS cost scenarios

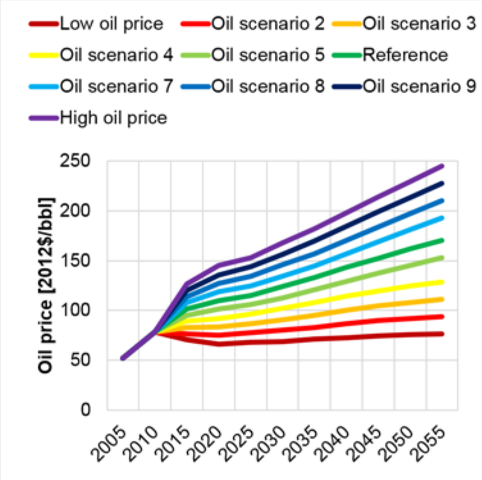


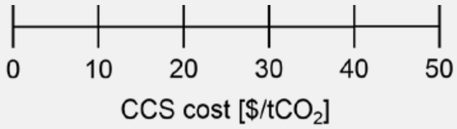
- Costs on lower end of spectrum arise from major technological breakthroughs and/or sale of CO_2 for EOR
- Cost range corresponds to IPCC estimates for coal IGCC power plants
- Cost estimates vary since CCS has not yet been demonstrated at meaningful scale
- CCS costs applied uniformly across system here

Nested sensitivity analysis

- Examined 126 sensitivities representing combinations of:
  - CO_2 constraints
  - oil prices
  - CCS costs







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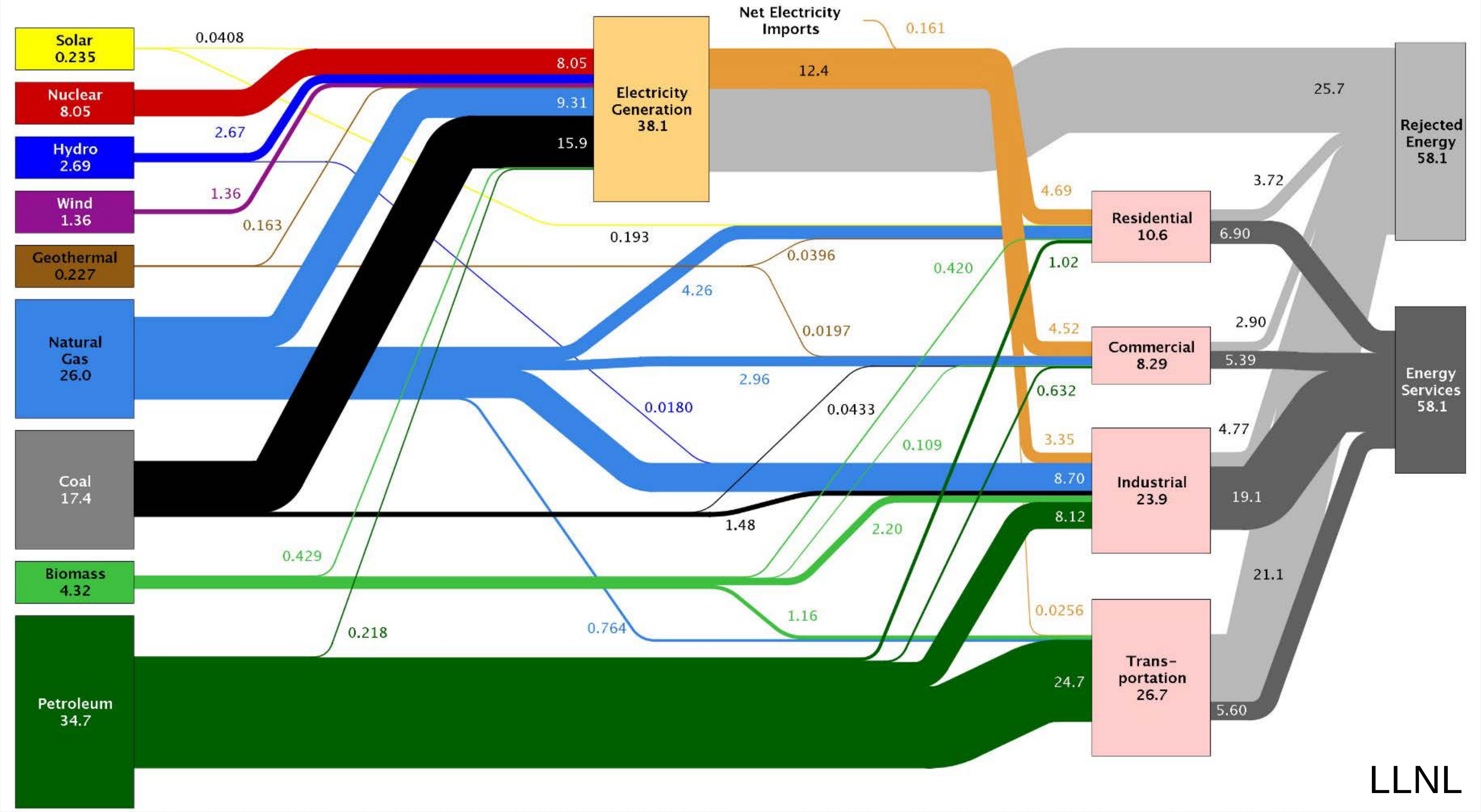
For reference…

- U.S. electricity generating capacity ~**1000 GW**
  - capacity factor for overall fleet ≈ 50%
- Use ~7 billion barrels of liquid fuels per year
  - energy consumption rate equivalent to ~**1300 GW**



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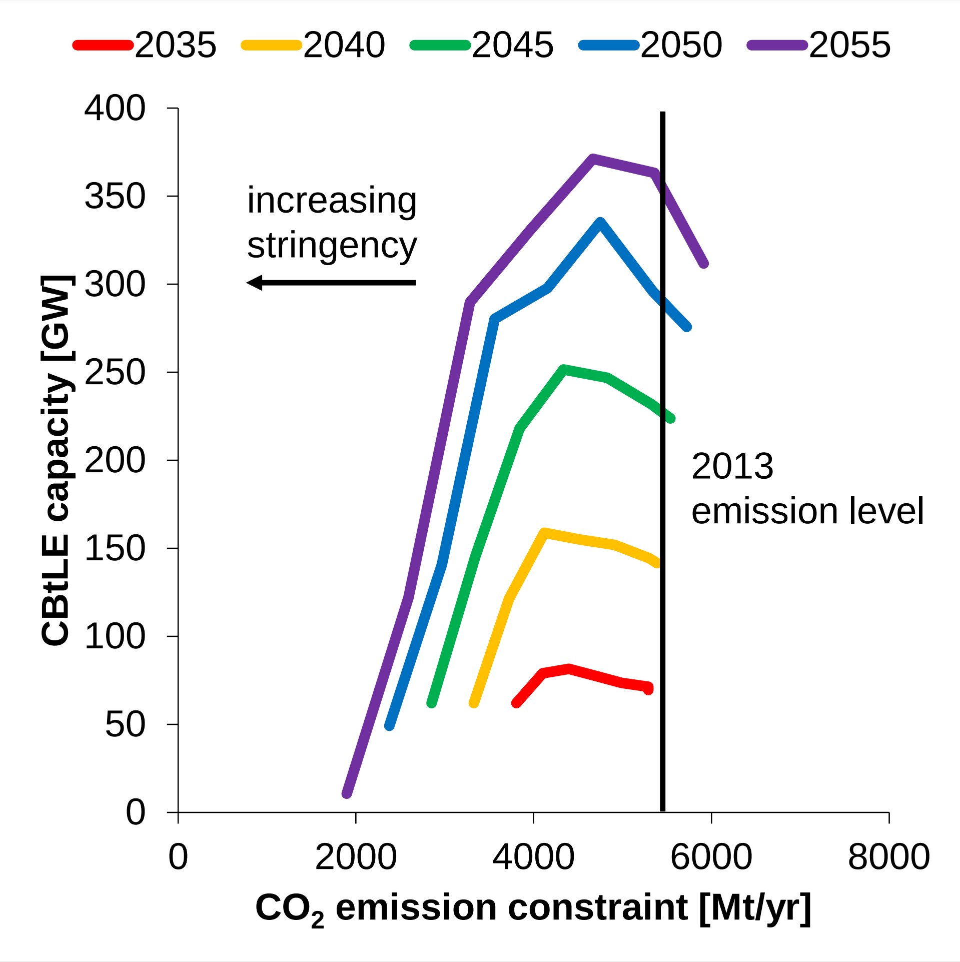
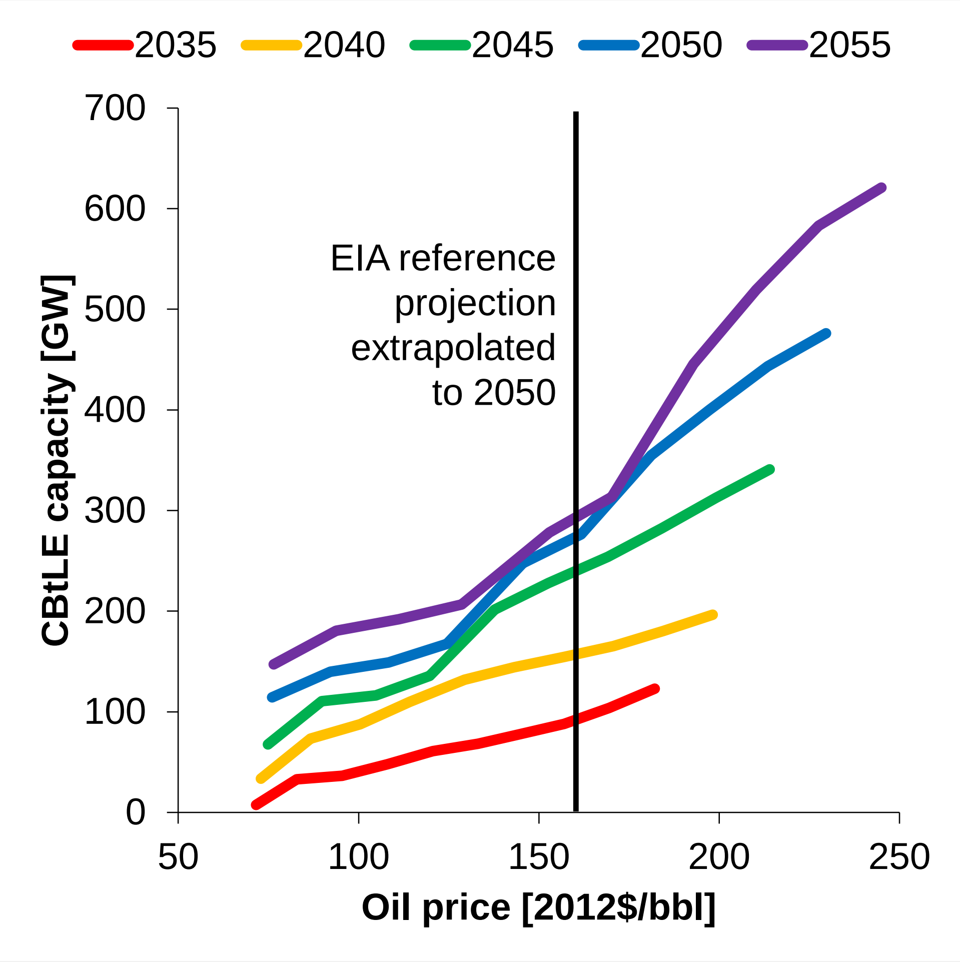
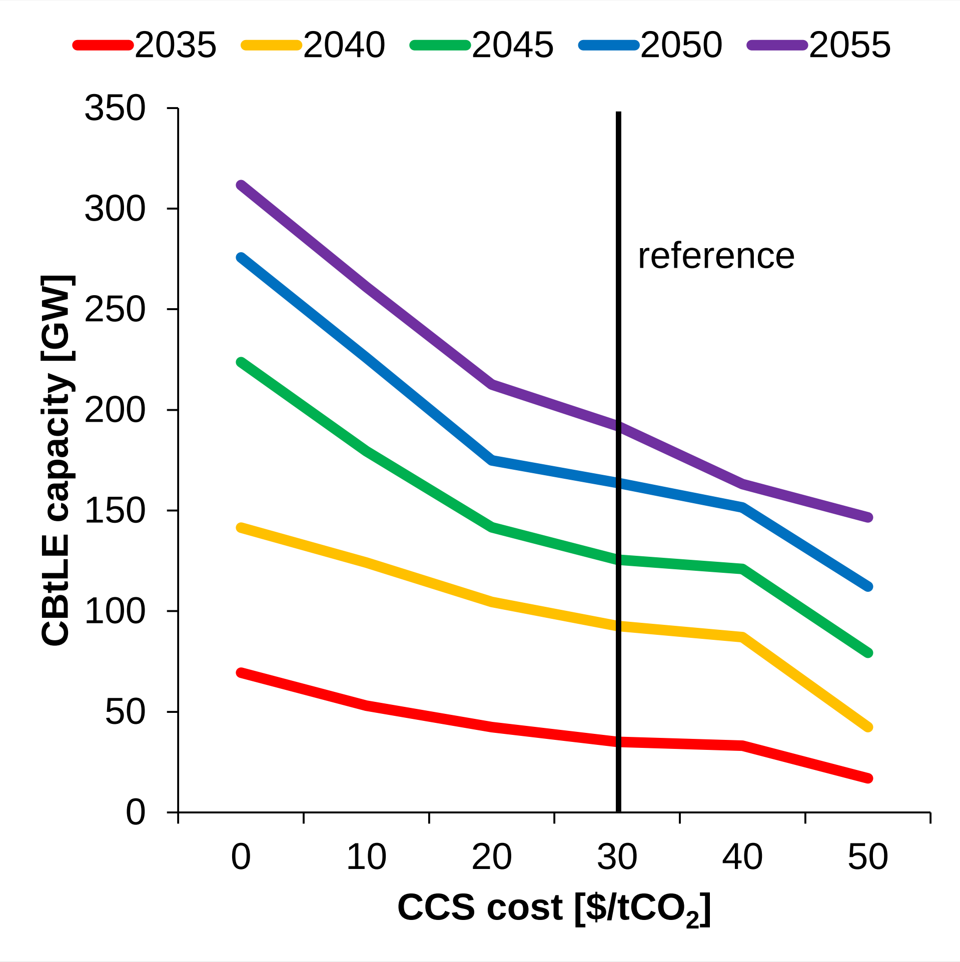
CBtLE not competitive in deep decarbonization scenarios



CBtLE capacity increases with the price of oil



CBtLE capacity decreases with the cost of CCS



Nested sensitivity analysis results

CBtLE capacity (in GW) in the year 2050. BAU = "business-as-usual"

Oil price scenario	CCS cost [$/t$CO_2$]	CO_2 reduction scenario						
		BAU	10%	20%	30%	40%	50%	60%
High	0	476	483	485	487	366	213	89
	10	434	440	448	459	353	165	81
	20	389	401	414	427	319	149	73
	30	354	357	384	393	284	118	60
	40	301	336	353	358	227	101	49
	50	277	287	309	296	205	70	35
Reference	0	276	296	335	298	280	141	49
	10	226	258	294	272	206	119	33
	20	175	199	243	239	157	95	27
	30	164	175	192	178	86	47	24
	40	152	142	149	101	49	23	18
	50	112	95	104	67	29	0	6
Low	0	114	120	122	124	64	16	0
	10	81	115	120	117	32	0	0
	20	60	87	105	81	2	0	0
	30	33	39	62	25	0	0	0
	40	5	17	23	2	0	0	0
	50	3	1	0	0	0	0	0

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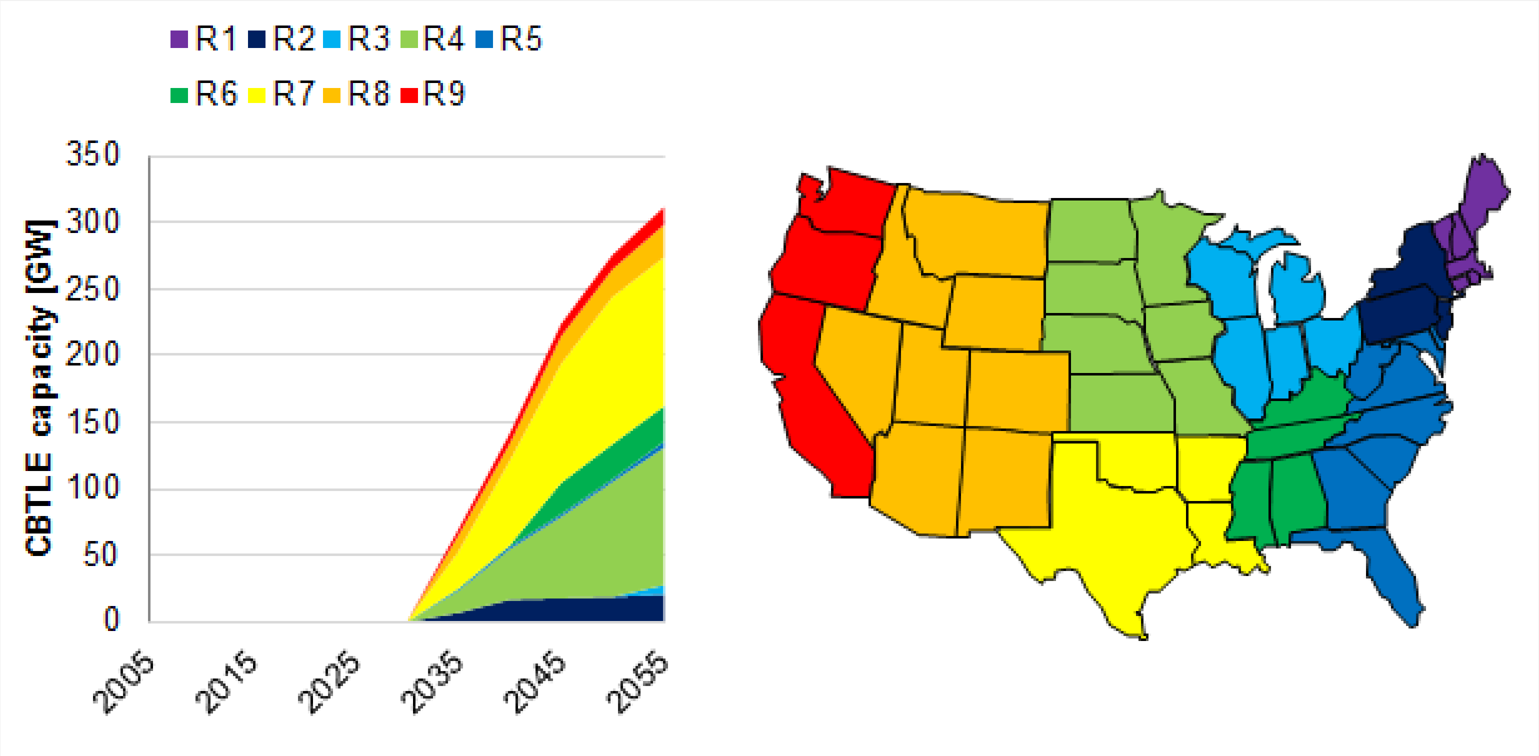
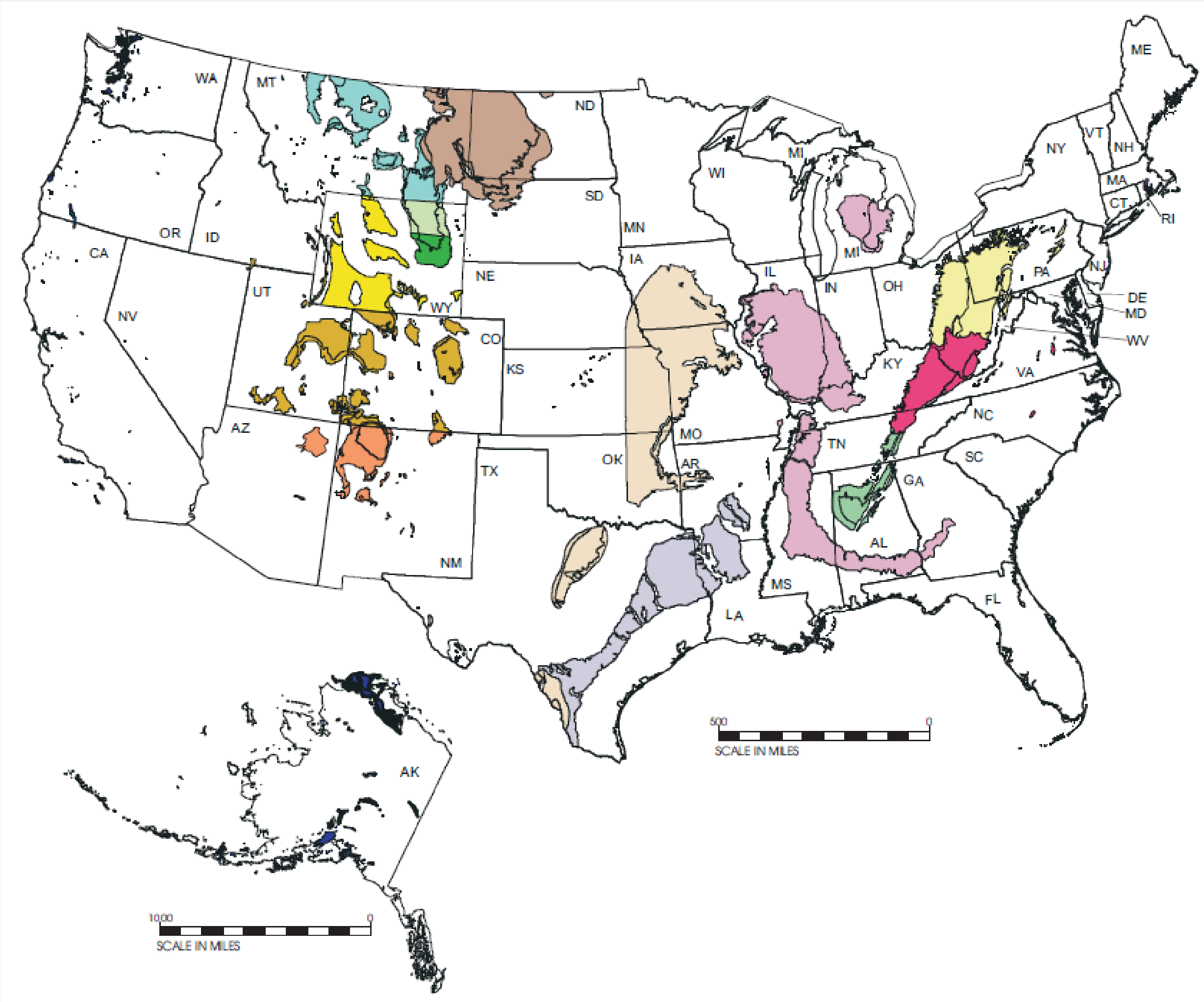
Reference case: most CBtLE built between Miss. River and Rocky Mtns



Coal supply regions



Region	Code	Color
Northern Appalachia	NA	
Central Appalachia	CA	
Southern Appalachia	SA	
Eastern Interior	EI	
Gulf Lignite	GL	
Western Interior	WI	
Dakota Lignite	DL	
Western Montana	WM	
Northern Wyoming	NW	
Southern Wyoming	SW	
Western Wyoming	WW	
Rocky Mountain	RM	
Arizona/New Mexico	ZN	
Pacific Coast	PC	

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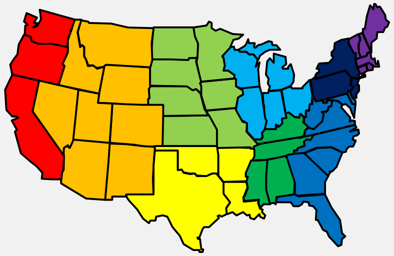
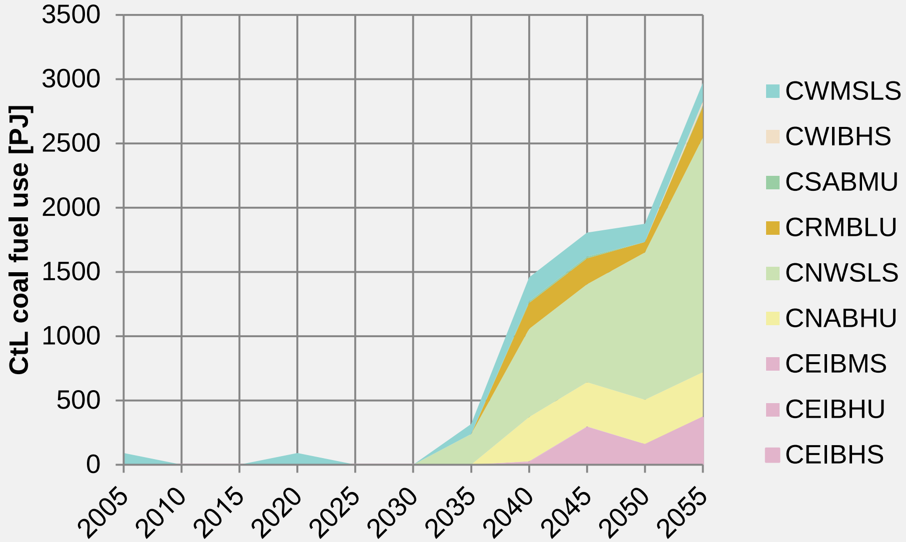
High CBtLE capacity in R4/R7 due to access to cheap and plentiful coal

Region	Production [short ton/year]				Consumption [short ton/year]				Coal price	Heat content
	Lignite	Subbituminous	Bituminous	Total	Lignite	Subbituminous	Bituminous	Total	[$/ton]	[Btu/lb]
1						319,684	2,491,060	**2,810,744**	88.32	12317
2			52,384,250	**54,718,802**		779,974	33,187,603	**35,855,829**	55.67	11131
3			111,533,858	**111,533,858**		100,585,819	80,773,207	**181,359,026**	47.54	10009
4	27,528,666		437,451	**27,966,117**	21,543,244	104,960,805	515,969	**127,020,018**	28.75	8351
5			141,673,204	**141,673,204**		12,448,802	95,089,604	**108,209,680**	78.89	11770
6	2,952,818		111,273,190	**114,226,008**	3,168,927	23,323,951	57,117,318	**83,610,196**	57.23	10657
7	48,149,354		1,152,094	**49,301,448**	45,758,241	99,385,448	1,042,599	**146,186,288**	31.88	7956
8	296,454	447,747,824	65,618,879	**513,663,157**		72,034,993	30,838,182	**102,873,175**	34.52	9388
9		2,052,086		**2,052,086**		5,554,339	147,631	**6,429,850**	37.63	8639

	Avg 2012 sale price	Sulfur content	Moisture content	Carbon content	Heating value
	[$/ton]	[weight %]	[weight %]	[weight %]	[Btu/lb]
Lignite	19.60	0.4	39	25-35	6900
Subbituminous	15.34	2	10.0-45	35-45	9000
Bituminous	66.04	0.7-4.0	2.2-15.9	45-86	12000
Anthracite	80.21	0.6-0.8	2.8-16.3	86-97	13000



Most CtL coal comes from Northern Powder River Basin in Wyoming



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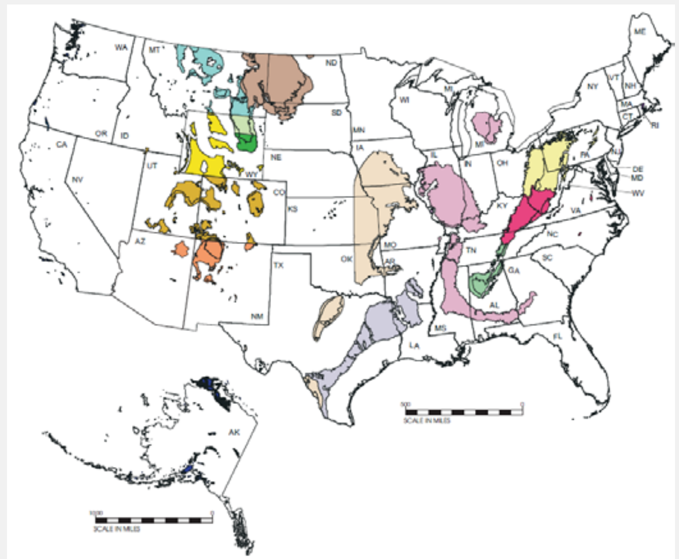
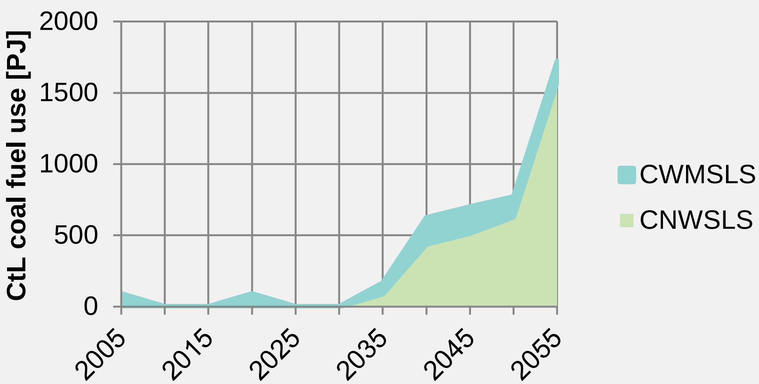
C	Region	Coal type	Sulfur content	Mine type
	NA, CA, SA, EI, GL, WI, DL, WM, NW, SW, WW, RM, ZN, PC	Lignite (L) Sub-bituminous (S) Bituminous (B) Premium (P) Gob (G)	Low (L) Medium (M) High (H)	Surface (S) Underground (U)

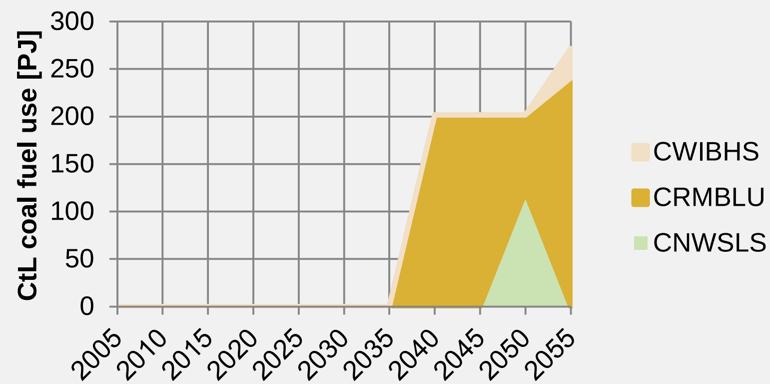
Regions use coal from nearby sources



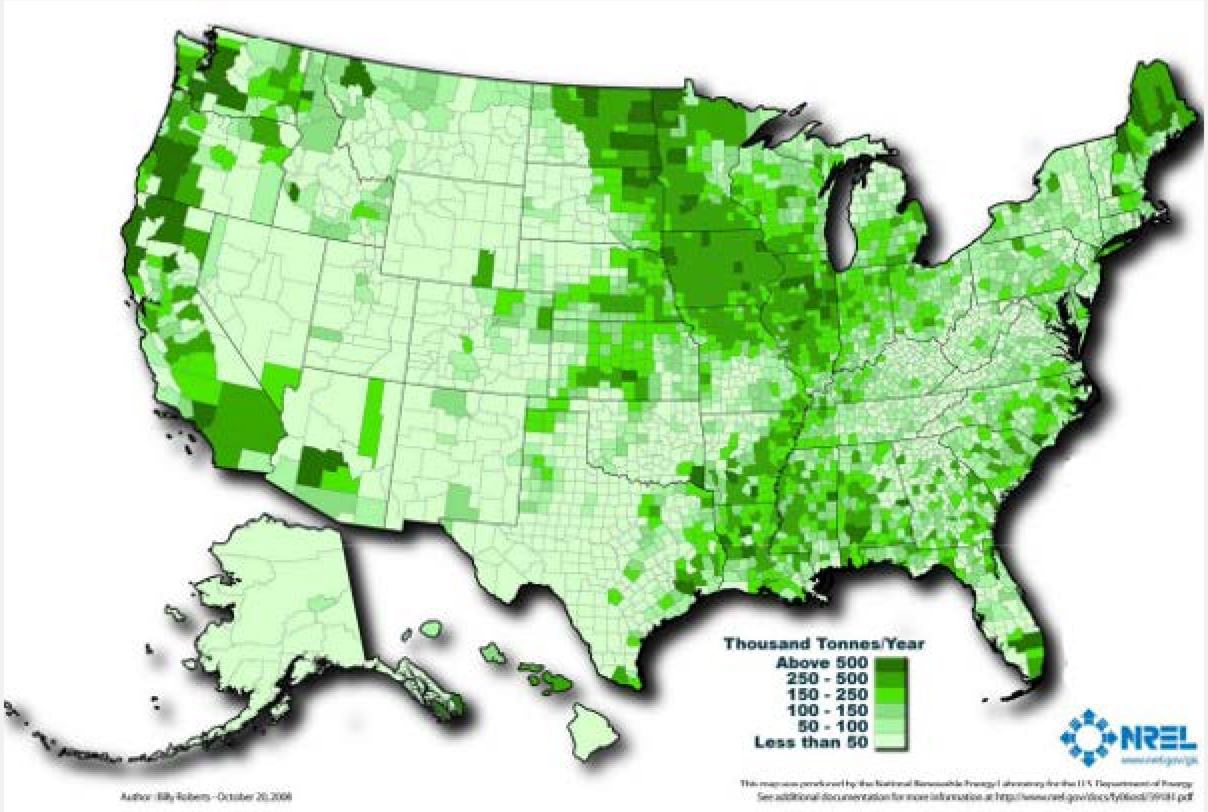
Region 4



Region 7



Biomass production concentrated in Midwest and South



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Conclusions

- CBtLE most competitive in scenarios with:
  - little to no CO_2 constraint
  - higher oil prices
  - lower CCS costs
- Within examined parameter ranges, CBtLE most sensitive to price of oil
- Most CBtLE capacity built in Great Plains and Midwest
  - proximate to coal-producing regions & low coal prices
  - high biomass production
- Very little CBtLE capacity in New England and West Coast
  - isolated from coal-producing regions & high coal prices

Conclusions

- CBtLE appears in baseline scenario
  - reference oil scenario + no new carbon policies
- CBtLE configuration here accepts 30% biomass as input and captures 85% of CO_2 output stream
  - this configuration is almost completely absent in deep decarbonization scenarios in MARKAL
- Technological advances could improve the competitiveness of CBtLE
  - more sustainably-sourced biomass input
  - higher CO_2 capture
  - lower costs

Future work

- Examine additional environmental consequences
  - e.g., water withdrawal/consumption rates
    - water use in the production of Fischer-Tropsch fuels is significantly higher than in conventional gasoline/diesel
      - could serve to constrain CBtLE development?
- Develop a supply curve for CCS cost
  - account for heterogeneity associated with different sites/scales
- Conduct analysis at finer geographic levels

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Thank you

- Questions?