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Comparative net energy analysis of renewable electricity and carbon capture and storage

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Supplementary Information

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Supplementary Tables

Supplementary Table 1 Comparison of Current Installed Base of Scalable Renewables and Carbon Capture. The 2016 installed peak Capacity (GW_p) for CCS powerplants, scalable renewables (sRE) combining wind and photovoltaics (PV) and biomass indicates the significant gap in favor of sRE. The growth rates needed to reach the installed contribution calculated in the IEA 2DS (2 degree scenario) targets also shows the very high growth required for CCS. (Authors' calculations using data sources: refs.[1], [2])

	Installed Base (GWp)		IEA 2DS Projections (GWp)	Observed Annual Growth Rate	Required Annual Growth rate to achieve 2DS target	Share achieved
Year	**2012**	**2016**	**2050**	**2012-16**	**2050**	**2016**
Power CCS	0	0.11	964	-	30.6%	0.01%
Scalable RE (PV and Wind)	370	670	8785	20.27%	7.8%	7.63%
Biomass	52	65	440	6.25%	5.8%	14.77%

Supplementary Table 2 List of Abbreviations and Symbols

Abbreviation/ Symbol	Units	Acronyms	Notes
sRE		Scalable Renewable Energy	Solar and wind systems
CCS		Carbon Capture and Storage	
CCUS		Carbon Capture Utilization and Storage	
EROEI		Energy Return on Energy Invested	**[Eq. 1]** The ratio of energy output over a project lifetime over the energy invested to construct and operate it
ESOI		Energy Stored On Invested	**[Eq. 7-12]** The ratio of electrical energy delivered from an energy storage system over its lifetime to the energy required to construct it.
IGCC		Integrated Gasification Combined Cycle	Coal powerplants that gasify the feeder coal prior to combustion; Offers higher overall efficiency compared to PC by deploying a combined gas and steam turbine system at the expense of higher upfront costs and system complexity. On paper they perform better energetically but in practice their complexity is a liability in commissioning them.
NGCC		Natural Gas Combined Cycle	
PC		Pulverized Coal	Conventional coal power plants

O&M		Operations and Maintenance	Referring to monetary and energetic expenses related to powerplant post-construction activities
P2X		Power to chemical storage X	
P2H		Power to hydrogen	
EOR		Enhanced Oil Recovery	A promising avenue for CCUS
		EROEI categories	
$EROEI_{el}$	$\frac{kWh_e}{kWh_{th}}$		Electrical energy generated during the lifetime of the project per unit of embodied and operational *primary* energy input. **[Eq. 3 for fossil plants]**. It penalizes projects that can utilize a large share of renewable electricity when being manufactured esp. PV.
$EROEI_{disp}$	$\frac{kWh_e}{kWh_{th}}$		$EROEI_{el}$ referring to sRE that includes the storage investment and potential curtailment to make them grid dispatchable
$EROEI_{CCS}$	$\frac{kWh_e}{kWh_{th}}$		**[Eq. 4-6]** $EROEI_{el}$ referring to CCS projects that includes the CCS investment and output losses
$EROEI_{th}$	$\frac{kWh_{th}}{kWh_{th}}$		Referring to the thermal energy content of the fossil fuel combusted for power generation
		Parameters/Symbols	
R		Fuel to capital ratio	**[Eq. 6]** Reference ratio of fuel to capital and non-fuel operating energetic costs of the conventional plant
CR	%	Capture ratio	Ratio of CO2 captured from the total CO2 in the flue-gas stream
E_{out}	kWh_e	Energy output	The electric energy output from the considered systems
E_{in}, E_{cap}, $E_{O\&M}$, E_f	kWh_e	Energy investment	Energy input or investment for: the construction (E_{cap}), operation and maintenance ($E_{O\&M}$), and fuel procurement (E_f)
E_{th}	kWh_{th}	Energy thermal	Thermal energy content of the fuel
L	*Years*	Lifetime	Usable lifetime of the energy project
λ	#	Storage Cycles	Number of charge discharge cycles of an energy storage system
u		Storage power adjustment	**[Eq. 8]** For storage systems that have significantly different energetic costs and scale economies between adding power (charge and discharge rate) and storage capacity. Primarily applicable for chemical, thermal or mechanical storage.
η		Efficiency	Process efficiency. For energy storage represents the roundtrip efficiency from electricity out to electricity in and for fossil power plants its thermal efficiency (electricity out over thermal energy of fuel)
f_{cap}	%	Capital energy penalty	Ratio of the additional capital embodied energy to total energy input
f_{op}	%	Operational energy penalty	Ratio of the reduction in net electricity output with CCS over the net electricity output without CCS for constant fuel flow.
cf		Capacity factor	Ratio of time that the power plant would need to operate at its full rated capacity over a time period in order to reach the same cumulative output
P	kW_e	Rated power output	Powerplant or storage system max electricity output power
C	kWh_e	Energy storage capacity	Maximum energy storage system potential
$s_{O\&M}$		O&M share	Ratio of annual O&M to capital costs
φ		Storage fraction	Share of electricity supply directed to the storage system over the total generation
k		Curtailment fraction	Share of energy supply curtailed – i.e. wasted.
ε	$\frac{kWh_e}{kW}$	Embodied Energy intensity	Unit embodied energy intensity of capital equipment

Supplementary Table 3. Summary of Operational and Capital Penalties Reported. The range of sources create a reasonable bracket for the expected potential range of capital (f_{cap}) and operational (f_{op}) energy penalties in comparison to equivalent non-CCS powerplants. (derived from author calculations and primary sources indicated in [3])

PC	**USDOE**	**EPRI**	**Alstom**	**IEA**	**GCCSI**	**ZEP**	**min**	**max**
Year	2013	2013	2011	2014	2011	2011		
Conventional Net Plant HHV Efficiency (%)	39.3	39	44.4	42.3	39.1	44.2		
CCS Net Plant HHV Efficiency (%)	28.4	27.4	36.1	33.8	27.2	36.5		
f_{op}	**27.7%**	**29.7%**	**18.7%**	**20.1%**	**30.4%**	**17.4%**	**17.4%**	**30.4%**
Conventioanl Plant cost (2013US$/kW)	1752	2496	2104	1883	2017	2290		
CCS Plant cost (2013US$/kW)	3099	4368	3597	3605	3641	3608		
f_{cap}	**56%**	**53%**	**58%**	**73%**	**56%**	**48%**	**47.5%**	**73.1%**
PC oxy-combustion	**USDOE**	**USDOE**	**EPRI**	**EPRI**	**EPRI**	**IEA**		
Year	2010	2010	2011	2011	2011	2014		
Conventional Net Plant HHV Efficiency (%)	38.7	38.9	39	39	39	42.2		
CCS Net Plant HHV Efficiency (%)	31	30.1	31.5	31.5	31	34.1		
f_{op}	**19.9%**	**22.6%**	**19.2%**	**19.2%**	**20.5%**	**19.2%**	**19.2%**	**22.6%**
Conventioanl Plant cost (2013US$/kW)	2560	2681	2613	2613	2613	2455		
CCS Plant cost (2013US$/kW)	4278	4829	5251	5242	5372	4661		
f_{cap}	**54%**	**62%**	**82%**	**81%**	**84%**	**73%**	**53.8%**	**83.9%**
IGCC	**USDOE**	**USDOE**	**USDOE**	**EPRI**	**GCCSI**			
Year	2013	2013	2013	2013	2011			
Conventional Net Plant HHV Efficiency (%)	39	39.7	42.1	38.3	41.1			
CCS Net Plant HHV Efficiency (%)	32.6	31	31.2	29.9	32			
f_{op}	**16.4%**	**21.9%**	**25.9%**	**21.9%**	**22.1%**		**16.4%**	**25.9%**
Conventioanl Plant cost (2013US$/kW)	2114	2035	2359	3224	2752			
CCS Plant cost (2013US$/kW)	2885	2997	3385	4264	3587			
f_{cap}	**30%**	**37%**	**32%**	**25%**	**24%**		**23.6%**	**36.9%**
NGCC	**USDOE**	**IEA**	**IEA**	**Rubin**	**USDOE**	**EPRI**		
Year	2011	2012	2012	2012	2013	2013		
Conventional Net Plant HHV Efficiency (%)	50.5	53.2	53.2	50	50.2	48.7		
CCS Net Plant HHV Efficiency (%)	42.9	46.1	47	42.6	42.8	42.4		

f_{op}	**15.0%**	**13.3%**	**11.7%**	**14.8%**	**14.7%**	**12.9%**	**11.7%**	**15.0%**
Conventioanl Plant cost (2013US$/kW)	935	1177	1177	808	820	1378		
CCS Plant cost (2013US$/kW)	1843	2599	2160	1422	1717	2626		
f_{cap}	**82%**	**105%**	**74%**	**65%**	**93%**	**79%**	**64.7%**	**104.7%**

Supplementary Table 4 Limit Cases for scalable renewable Energy Return on Investment to Exceed CCS. The table presents numerically the parts of Figure that for which EROEIdisp of sRE Exceeds the $EROEI_{CCS}$ of powerplants under operating assumptions of capacity factor cf =85% and carbon capture ratio CR=90%.

CCS Technology	EROEI fuel, elec, CCS	Storage Case	$EROEI_{el}$ min	Storage fraction (%)	$EROEI_{el}$	Max Storage fraction (%)
NGCC High	87, 31, **21.3**	Battery	21.3	0	40	26.2
		Batt + Curt	22.9	0	40	22.3
		P2H	21.3	0	32.2	35
		Battery	21.3	0	30	16.3
		P2H	21.3	0	30	29.9
		Batt + Curt	22.9	0	30	12.4
		PHS	21.3	0	23.5	35
		PHS	21.3	0	23.5	35
NGCC Mid	53.5, 21.4, **15.6**	Batt + Curt	20	11.3	33.8	35
		Batt + Curt	16.8	0	30	30.6
		Battery	20	16.5	29.4	35
		Battery	15.6	0	29.4	35
		P2H	20	24.8	22.6	35
		P2H	15.6	0	22.6	35
		PHS	15.6	0	17	35
PC High	58, 13.5, **8.4**	Batt + Curt	9	0.4	12.9	35
		Battery	9	8.7	11.6	35
		P2H	9	8.7	11.6	35
		PHS	9	30.8	9.1	35
IGCC High	58, 11.5, **8.0**	Batt + Curt	9	5.2	12.2	35
		P2H	9	13.8	11.1	35
		Battery	9	14.2	11	35
PC Mid	40.5, 10.6, **6.8**	Batt + Curt	9	25.4	9.8	35
		P2H	9	31	9.4	35
IGCC Mid	40.5, 9.2, **6.6**	Batt + Curt	9	30.4	9.4	35
		P2H	9	34.8	9	35

Supplementary Table 5 Example Calculation of sRE and Storage Portfolio EROEI$_{disp}$ Estimate (base data source: European system as described[4])

	Net supply (GWh)	Gross Supply (GWh)	Shares (α_i)	Storage efficiency	Storage fraction (φ_j)	EROEI / ESOI
System Demand	5212.5					
1.PV	1407.4	1667.1	32.9%			18
2.Wind	2866.9	3396.0	67.1%			35
Storage Out	417.0					
Biomass	521.3					
Curtailment		104.3				
Storage in		684.6				
Battery			55%	83%	5.5%	11
PHS			25%	80%	2.6%	249
P2H			20%	30%	5.5%	24
System EROEI$_{disp}$ (Eq. S11)	**21.9**					

Supplementary Note 1

Non-energetic Biophysical Considerations

Our approach focused on comparing CCS and RE for electricity generation. As such, it is not applicable to: (i) CCS processes associated with non-electric, energy conversion practices, such as processing of oil and gas, (ii) industrial processes like steel or cement production because the primary functional output is not electricity, (iii) bio-energy CCS (BECCS) and other direct atmospheric capture (DAC) technologies where the atmospheric carbon removal is the primary objective and the energy output is an ancillary co-product, and (iv) "*carbon capture and utilization*" (CCU) i.e. the capture and subsequent use of the CO_2 stream for industrial uses like the manufacture of fuels or chemicals some of which have very limited CO_2 retention time. The following considerations though are applicable to all the above.

While net energy disadvantages create a critical problem in the choice of CCS energy technology, there exist a host of other factors related to scaling up to the levels necessary for the energy transition. We can group these factors within the general label of "biophysical constraints" operating for both RE and CCS. Here, it would be out of scope to analyze in depth these constraints, since the present paper is limited to a comparison of the EROEI of CCS and RE. However, we may note that, for CCS scaling, the impediments to scaling can be listed as (*i*) CCS scaling potential and the effects of fossil fuel resource depletion, (*ii*) location dependence on the availability of carbon storage reservoirs, (*iii*) the risk associated with reliance on its future deployment (for negative emissions), and (*iv*) the fact that CCS does not feasibly capture 100% of the carbon emission stream in the flue gas.

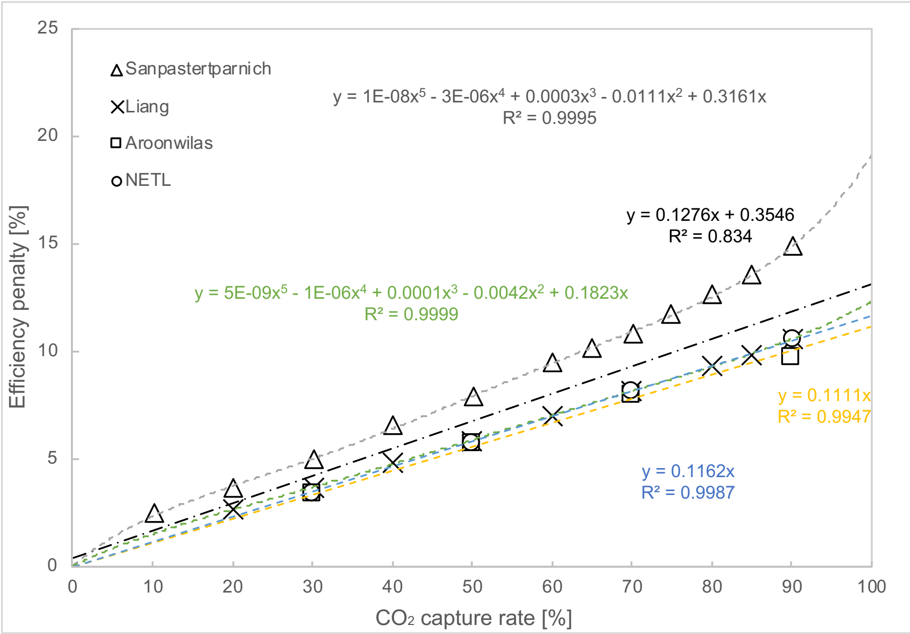
CCS in fossil fuel power generation, even in its best implementation, does not constitute a zero emissions system since the capture ratio has not yet been designed in concrete project plans to exceed 90% of the carbon emissions. In addition, there is a lack of successful pilot projects in diverse geographic locations. The projects that do proceed face significant cost overruns. Finally, there are limited available geologic locations and existing pipeline infrastructure dedicated to CO_2 transport, to allow for several regions to implement CCS. By 2016, the only commercially operational coal-fired CCS plant (110 MW at Boundary Dam, Canada) cost $1.3 billion and registers technical issues, while the major 584MW US project at Kemper Mississipi is expected to cost $6.5 billion instead of the planned \$2.4 billion and faced several cancellations[5]. These values, adjusted for inflation, exceed by more than three times the anticipated estimates shown in Table 1 at \$10,000/kW. Such achievements significantly diverge from the suggested trajectories for a large scale implementation potential[6], [7].

Given the net-energy disadvantages of coal-fueled CCS, NGCC with carbon capture may be seen as the more promising option. Yet, this neglects the issue of upstream fugitive emissions in the natural gas extraction and transportation system[8]. Also, if these plants are expected to support higher RE penetration their economics will be increasingly affected as their utilization factors would drop and it would be hard to economically justify the additional expense of a CCS facility for a plant that operates as load-follower that fills in the gaps rather than baseload.

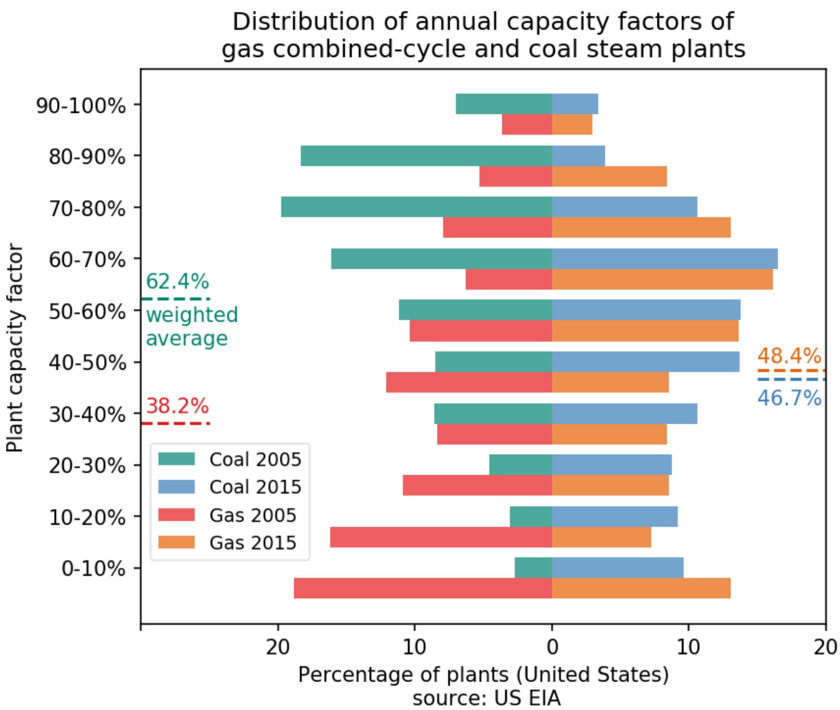
Carbon dioxide storage is in itself problematic for several reasons. The main technology proposed so far, geological sequestration of CO_2, may create serious problems since we are replacing non-reactive hydrocarbons with CO_2 which is a reactive (acidic) gas, potentially affecting the stability of the reservoir over long time spans. For this reason, it would be safer to transform CO_2 into inert, non-gaseous products. One such possibility is to transform CO_2 into solid carbon, which is technologically possible either by electrochemical methods[9] or as bio-char. The main problem associated with this concept is that solid carbon is a reactive solid that burns in air and, hence, it could always present a tempting fuel resource or be burned accidentally. These risks can only be mitigated by very deep burial, but the costs of burying a solid is much higher than pumping a gas in an existing reservoir. The last possibility is to transform atmospheric CO_2 into carbonates, which are stable and non-burnable, imitating a natural process called "silicate weathering" [10]. Unfortunately, this process occurs very slowly in nature. It could be accelerated by human intervention but, at present, there are only tentative proposals which appear very expensive and whose large-scale feasibility is debatable[10].

Regarding renewable energy, the biophysical constraints are related mainly to the availability of high quality resources at a regional level and mineral resources needed for the scaling up to the levels necessary for the energy transition. The regional RE constraints can be met through energy trade similarly to how energy trade distinguishes between energy importing and exporting countries today. Studies of 100% sRE-driven systems show that the majority of countries generally have the domestic resources to cover their energy needs with sRE [11] while trade makes these systems viable and more optimally distributed [12], [4]. The mineral depletion subject has also been examined. Solar photovoltaic, a centerpiece for scalable renewable energy, uses only elements abundant in the earth's crust: mainly silicon and aluminum and additional traces of phosphorous and boron. The exception is the use of silver for the back contacts, but this is a substitutable and not critically important factor for the technology scaling[13]. Other renewable energy technology have different material constraints, for instance a segment of the current generation of wind turbines relies on rare-earth magnets but there are alternatives which are currently commercial. A study that estimated material limits connecting them to the system EROEI recognizing that to retrieve them would require increasing energy resources found that while current and projected expansion is within reach, there are energetic limits to it[14]. The landscape is similar for storage options with lithium being of some concern [15] but other options like thermal storage and NaS batteries rely on much more abundant minerals. Clearly no system fossil or renewable can expand without limits on a finite planet. The objective is to find the right balance for a sustainable steady-state energy system to which our paper presents a small contribution.

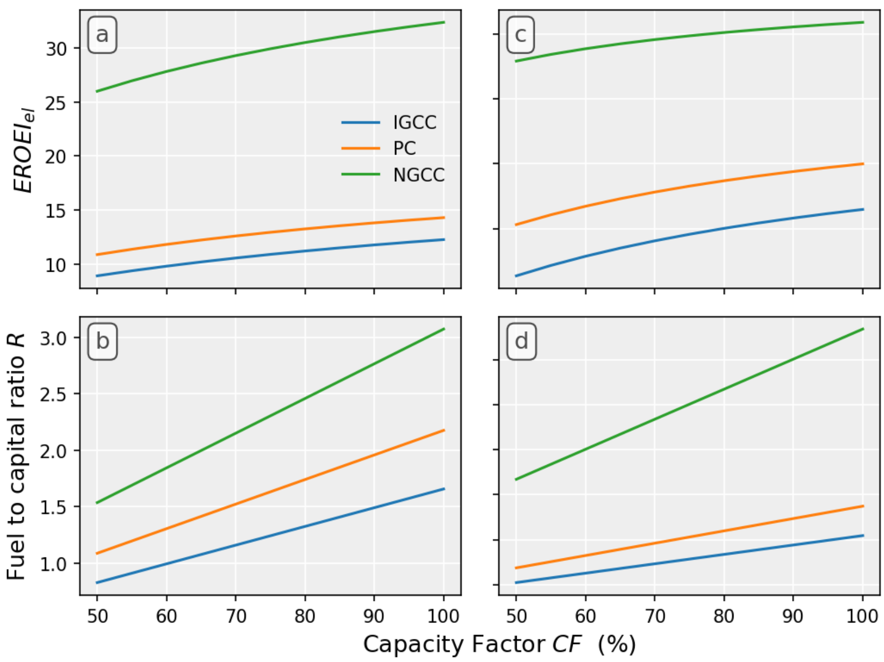
Supplementary Figures



Supplementary Figure 1 Capture Ratio (CR) effect on Power Plant Efficiency (data sources: [16], [17], [18], [19])



Supplementary Figure 2 Distribution of Fossil Powerplants Capacity Factors in the United States (Data source [20]). The left-hand side from the vertical axis represents the distribution of coal (green) and natural gas (red) powerplants based on their average annual capacity factor in 2005. The right-hand side shows the same distribution for year 2015 (shown in blue for coal and amber for natural gas). The mean capacity factors are shown on the correspondent edge. We notice that the average capacity factor of natural gas plants became higher than coal plants between 2005 and 2015.



Supplementary Figure 3 Normalized Relationship of EROEI electric (a, c) and the fuel to capital ratio (b,d) to capacity factor (cf). The three lines in each panel represent the variation for integrated gasification combined cycle coal (IGCC), pulverized coal (PC), and combined cycle natural gas (NGCC) plants. Panels a and b use 58 as the fuel EROEI (thermal) for coal and 87 for gas, while panels c and d use 23 and 20, respectively.

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