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Coal with Carbon Capture and Sequestration is not as Land Use Efficient as Solar Photovoltaic Technology for Climate Neutral Electricity Production

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Avoiding climate destabilization caused by greenhouse gas (GHG) emissions, requires climate-neutral electricity sources. It has been proposed that the GHG emissions from coal-fired power plants can be offset by carbon capture and sequestration or bio-sequestration. However, solar photovoltaic (PV) technology has recently declined so far in costs it now offers both technical and economic potential to offset all of coal-fired electricity use. PV only emits GHGs during fabrication and not during use. To determine which technical solution to climate-neutral electricity generation should be preferred, this study aggregates and synthesizes life cycle analysis studies for exergy, GHG emissions and land transformation for climate-neutral electricity. The results show that because of lower exergy efficiencies coal plants emit 13–18 times more GHG and transform 5–13 times more land than PV. Optimal bio-sequestration of coal-fired GHG requires 62% of U.S. arable land or 89% of all U.S. land with average forest cover. Carbon capture and storage and enhanced oil recovery can improve coal performance, but for all cases the results clearly show that PV is a far more effective use of land. Overall, for the first time this study found climate-neutral photovoltaic farms are a preferred solution to climate-neutral coal fired electricity generation.

It is now well established that global climate change is underway because of greenhouse gas (GHG) emissions dominated by anthropogenic energy production¹. This has negative impacts on natural and socio-economic systems^{2,3}. GHG emissions increase global temperatures⁴, which in turn increase sea levels⁵, extinction rates among animals⁶ and also harms human health^{7,8} and the stability of traditional power generation⁹. GHG emissions are dominated by carbon dioxide (CO₂)¹⁰ with 40% of CO₂ emissions coming from traditional electrical power generation¹¹. There is a clear need to mitigate climate change by reducing emissions during energy generation^{12,13}. This can be accomplished in part through the use of climate-neutral renewable and traditional power generation^{14–17}.

Climate-neutral electricity generation, where the life cycle CO₂ equivalent of all GHG emissions from an energy source are eliminated, would have the largest single potential benefit to mitigating climate change in the future as transportation moves toward electrification. Although, selecting a climate-neutral power source is challenging, the concept of exergy can be used to guide decision making. Exergy can be thought of as the useful energy available and is advantageous for comparing systems with different grades of energy¹⁷. Energy efficiencies are misleading because they lack proper accounting for sources of waste heat and irreversibility. For example, low-temperature heat from solar thermal collectors is less useful than electricity from solar photovoltaic (PV)

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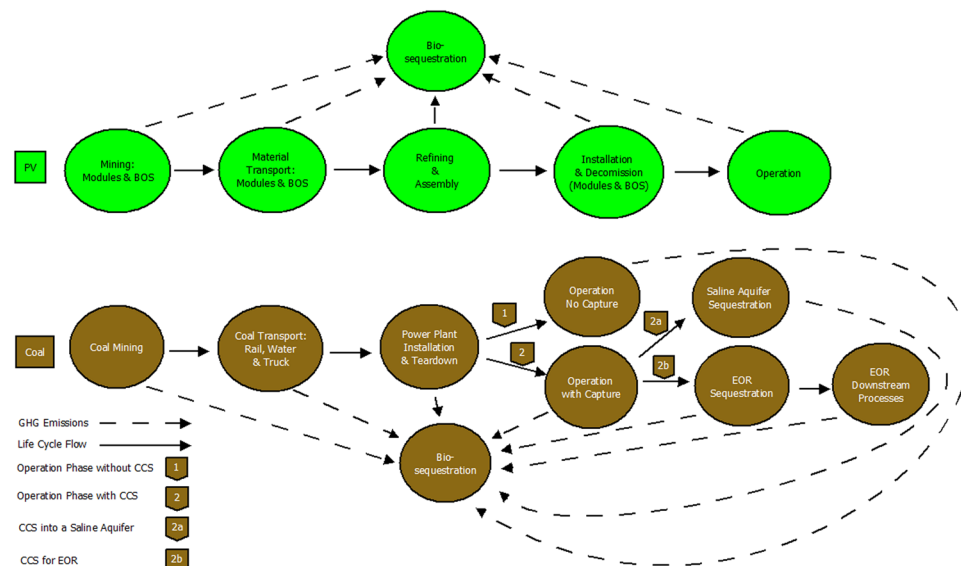


Figure 1. LCEA boundary scope for climate-neutral PV and pulverized coal electricity production. The solid arrows represent the flow of the life cycle, the dashed lines represent the $\text{CO}_{2\text{eq}}$ of the GHG emissions uptake by bio-sequestration and the labels detail various the scenarios for the coal lifecycle.

systems, although PV efficiencies are less than that of solar thermal systems¹⁸. Energy cannot be lost, while in real systems these irreversible entropy losses are quantified by exergy efficiency^{19,20}.

The largest producer of electricity is coal²¹ whose $\text{CO}_{2\text{eq}}$ emissions demand some form of carbon capture and sequestration (CCS) in order to be climate neutral. Typically, CCS is the capture and separation of CO_2 and subsequent compression and transport to storage locations such as saline aquifers^{22,23}. A popular form of CCS utilizes enhanced oil recovery (EOR), which pumps CO_2 into an operational oil and gas reservoir to displace more oil and gas^{22,24}. However, another form of CCS is the planting of biomass to permanently absorb and store carbon either in itself or the soil²⁵, referred to here as bio-sequestration. All of these processes have their own downstream emissions and coupled with the remainder of life cycle emissions, climate neutral coal-fired electricity generation requires large areas of land, especially for bio-sequestration²⁶.

On the other hand, solar PV has the greatest potential to scale to provide for sustainable future among renewable sources²⁷, but demands large surface areas during operation²⁸. PV also has embodied energy, which results in upstream emissions. So climate-neutral PV also requires land transformation for bio-sequestration.

The purpose of this study is to determine if is a better use of land and energy to produce climate neutral electricity with coal (and some form of carbon sequestration) or PV. Several life cycle analysis (LCA) studies are aggregated here to determine the preferred approach to climate neutral electricity generation. This study compares exergy, GHG emissions and land transformation needed for climate-neutral solar PV and climate-neutral pulverized coal with and without utilizing various forms of CCS. The climate-neutral status of a given technology is attained through a combination of bio-sequestration and CCS in saline aquifers or oil and gas reservoirs during EOR. PV and coal-based climate neutral energy solutions are analyzed using power plants with equivalent lifetime electricity output in a complete comparative analysis using aspects of exergy analysis and LCAs, summarized in Fig. 1.

Climate-Neutral Coal Plants

Combustion of coal for electricity produces CO_2 directly and a method is needed to eliminate the effect of these emissions on the atmosphere and the climate. The coal plant analyzed has a 1GW nameplate capacity and a capacity factor of 85%, which produce 376 TWhrs over a 50 year lifetime. The natural environment has a substantial capacity to store carbon near permanently, referred to here as bio-sequestration²⁶, but they are land area intensive so several methods are analyzed to reduce this impact from coal.

The most common process to capture CO_2 from a coal plant uses monoethanolamine (MEA) post-combustion for flue gas separation. Membranes with one and two step sweeps, pre-combustion gasification, oxidation, solid sorbents, metal organic frameworks, diethanolamine (DEA) and methyldiethanolamine (MDEA) and others have been developed as well to separate CO_2 from coal flue gases. In order to be included in this analysis, at least 80% of the carbon had to be captured. These processes are energy intensive which derates electrical generation of a coal plant²⁹. In order to maintain the same output, it is assumed that more coal is combusted to offset the drop in efficiency with the addition of CCS. The captured CO_2 is compressed to a supercritical state, typically between 8.6–15.3 MPa, and transported through pipelines to the storage location³⁰. In order to theoretically offset the GHG emissions from the coal lifecycle, both with and without CCS, bio-sequestration is employed here, specifically switchgrass as it has the best rate of carbon uptake and sequestration potential²⁶.

Attempting to mimic natural carbon sequestration, CCS has received a lot of attention recently³¹. Globally, potential CO₂ storage in geological formations is between 200–2,000 Gt, with saline aquifers comprising the majority³². There are currently 16 active CCS projects globally, injecting 30.15 t_{CO₂}/yr with another 22 projects planned for the next 10–15 years³². Once CO₂ is sequestered in geological formations like saline aquifers and oil and gas reservoirs, it has to be monitored to quantify leakage³³, which also must be offset for climate neutrality. 13 of the 16 active projects employ EOR to partially or fully sequester the CO₂. However, as EOR can increase the productivity of an oil reservoir from 25–55% to 35–75%³⁴, the additional exergy output and CO₂ emissions from downstream processes like oil refining and combustion must be accounted for, which in turn demands further land transformation for bio-sequestration. The net exergy output of coal with CCS for EOR is 866 TWhrs over its lifetime.

Climate-Neutral Photovoltaic Farms

To compare directly to the coal plants, two fixed-panel solar PV farms are designed to similarly produce 376 TWhrs (PVs1) and 866 TWhrs (PVs2) over a 50 year lifetime³⁵ with a degradation rate of 0.49%/yr^{36,37}. Assuming a capacity factor of 18.3% and performance ratio of 0.89, this results in a nameplate capacity of 5.23 GW for PVs1 and 12.13 GW for PVs2. The embodied emissions from the PV farm can be roughly broken down to three main categories, modules, balance of system (BOS) and construction/decommission³⁸. The values for exergy, emissions and land transformation include the impacts from extraction of raw materials, transportation, refining to solar grade silicon, assembly of modules, construction of the PV farm and implementation of bio-sequestration for all emissions with switchgrass.

Results: Comparison of Exergy, Emissions and Land Transformation in 1GW-Equivalent Climate Neutral Photovoltaic and Coal Power Plants

This study compares the exergy, GHG emissions and land transformation needed for climate-neutral pulverized coal with and without utilizing various forms of CCS and climate-neutral solar PV.

Climate-neutral coal plants. Three scenarios for carbon sequestration are analyzed: 1) no carbon capture technology at the plant, and instead uses bio-sequestration to uptake the carbon entirely; and plant level carbon capture of at least 80% and pipe it to 2a) a saline aquifer with remaining emissions using bio-sequestration, or 2b) for use in EOR, with all remaining emissions using bio-sequestration.

The coal plant analyzed here has individual contributions to upstream activities from mining and transport of coal and the construction/decommission of the coal plant. Mining and transport account for the majority of exergy input emissions and land transformation with the tonnage of coal consumed by the plant being the main driver. Upstream activities of a coal plant without carbon capture requires 108 TWhrs of exergy input, emits 3.92×10^7 t_{CO₂eq} and transforms 17.8 kha of land for bio-sequestration. The addition of carbon capture technology pushes this to require 149 TWhrs, GHG emissions of 5.34×10^7 t_{CO₂eq} and transforms 22.7 kha^{39,40}. The carbon capture option requires more coal due to the lower efficiency plant.

During the operation of the coal plant, the effects of adding carbon capture technologies is studied. Additional coal input is used to offset the derating of the plant due to carbon capture to ensure a 1GW nameplate capacity. A typical state-of-the-art plant drops from an efficiency of 37% to 27% with the addition of carbon capture technology^{22,29,36,41,42}. If the upstream exergy input is subtracted from the exergy output, then the net efficiency drops to 27% without carbon capture and 17% with carbon capture. In power plants without carbon capture, 995 TWhr_{eq} of coal is required, resulting in 1.52×10^8 t_{coal}. GHG emissions total to 3.38×10^8 t_{CO₂eq}^{39,43}. The total land required is 361 kha, with bio-sequestration transforming 343 kha and the plant alone transforms 202 ha^{26,38,40}. The physical area required for the plant is considered constant with and without CCS.

In power plants with CCS, the exergy input from coal equates to 1370 TWhrs and emits 6.07×10^7 t_{CO₂eq} to the atmosphere^{44,45}. The total GHG emissions produced from both upstream and during operation are 4.52×10^8 t_{CO₂} with 3.38×10^8 t_{CO₂} going to storage. If the captured CO₂ is piped to a saline aquifer for sequestration, this results in the uptake of 1.18×10^8 t_{CO₂} that were released to the atmosphere for bio-sequestration^{38,44,45}. The slight discrepancy in uptake by bio-sequestration is from the emissions due to leakage. The total land transformation is 132 kha, with bio-sequestration requiring 109 kha alone^{9,26,31,38,40}.

In power plants with CCS for EOR, the subsequent downstream activities require 1400 TWh's of exergy input, which totals to 2.16×10^8 GWhrs and emit an additional 1.93×10^8 t_{CO₂eq} to the atmosphere. This means that 3.11×10^8 t_{CO₂eq} will need to be bio-sequestered^{32,38,39,43–45}, which necessitates 307 kha of total land transformation with 284 kha for bio-sequestration^{9,26,31,38,40,43,46}.

The downstream processes for EOR also produce additional exergy output. In order to give a direct comparison to PV, the exergy output from EOR-based refined product is combusted with an efficiency of 39%⁴⁷ to generate electricity. The total lifetime exergy output for the EOR scenario becomes 866 TWhrs net electricity. A more in depth breakdown of the exergy flow, emissions and land transformation for coal with various forms of CCS can be found in Tables 1 and 2.

Climate-neutral solar photovoltaic farms. The upstream exergy input, emissions and land transformation can be separated into three categories, modules, BOS and construction of the PV farm. The total exergy input is 20.0 TWhrs. The majority of GHG emissions occur upstream, totaling 8.92×10^6 t_{CO₂eq} and transforms 584 ha of land for bio-sequestration and the PV farm physical footprint^{38,39,48–50}.

The desired electrical output for PVs1 is 376 TWhrs over the 50 year lifetime. The exergy efficiency of the PV system is 12.1%^{51,52}, which is rather conservative, and together with the U.S. average solar irradiation of 15,000 GWh/ha-yr it provides the required exergy input of 4,330 TWhrs. Moreover, 8.69×10^4 t_{CO₂} are emitted from the

Life Cycle Phase	Source/Sink	Exergy _{in} (GWh)	Exergy _{out} (GWh)	Emissions* (t _{CO₂eq})	Land Transformation (ha)
Upstream without CCS	Mining	6.69×10^4 ^{22,29,36,42,56–60,62}		2.16×10^7 ^{39,43}	1.32×10^4 ^{40,48,64}
	Transport	3.17×10^4 ³⁹		1.76×10^7 ^{39,43}	4.32×10^3 ^{39,48,76}
	Construction	1.29×10^4 ^{39,63}		1.66×10^5 ^{39,63}	N/A
	Total	1.11×10^5 ^{22,29,36,39,42,56–60,62}		3.92×10^7 ^{39,43,63}	1.78×10^4 ^{3,40,48,64,76}
Upstream with CCS	Mining	9.21×10^4 ^{22,29,42,56–61}		2.94×10^7 ^{39,43}	1.82×10^4 ^{40,48,64}
	Transport	4.37×10^4 ³⁹		2.40×10^7 ^{39,43}	4.32×10^3 ^{39,48,66}
	Construction	1.29×10^4 ^{39,63}		1.66×10^5 ^{39,63}	N/A
	Total	1.49×10^5 ^{22,29,39,42,56–61,63}		5.34×10^7 ^{39,43,63}	2.27×10^4 ^{39,40,48,64,66}
Operation without CCS	Plant	9.95×10^5 ^{22,29,36,42,57,60,62}	3.76×10^5	3.38×10^8 ^{38,44,45,58}	2.02×10^2 ⁴⁸
Operation with CCS	Plant	1.37×10^6 ^{22,29,41,42,57,59–61}	3.76×10^5	6.07×10^7 ^{22,38,54,45,58}	2.02×10^2 ⁴⁸
Downstream without CCS	Bio-sequestration	2.57×10^8 ^{38,39,43–45,53,58,79,83}		-3.77×10^8 ^{38,39,43–45,58,63}	3.43×10^5 ^{38,39,43–45,53,58,63,74}
Downstream with CCS into a saline aquifer	Bio-sequestration	8.14×10^7 ^{10,22,31,32,38,39,42–45,53,58,63,79,83,96}		-1.18×10^8 ^{10,22,31,32,38,39,42–45,53,58,63,79,96}	1.09×10^5 ^{10,22,31,32,38,39,42–45,53,58,63,79,83,96}
	CO ₂ Conditioning	2.64×10^4 ^{41,79}		1.97×10^6 ^{10,32}	N/A
	CO ₂ Injection	1.57×10^3 ^{43,78}		N/A	N/A
	CO ₂ Leakage	N/A		3.53×10^6 ^{31,82}	N/A

Table 1. Overview of exergy flow, emissions and land transformation by life cycle phase in a climate neutral coal plant outputting 376 TWhrs of electricity over a 50 year lifetime. *Carbon sequestration as negative and carbon equivalent emissions as a positive numbers.

Life Cycle Phase	Source/Sink	Exergy _{in} (GWh)	Exergy _{out} (GWh)	Emissions* (t _{CO₂eq})	Land Transformation (ha)
Upstream with CCS	Mining	9.21×10^4 ^{22,29,42,56–61}		2.94×10^7 ^{39,64}	1.82×10^4 ^{40,48,64}
	Transport	4.37×10^4 ³⁹		2.40×10^7 ^{39,64}	4.32×10^3 ^{39,48,66}
	Construction	1.29×10^4 ^{39,63}		1.66×10^5 ^{39,63}	N/A
	Total	1.49×10^5 ^{22,29,39,42,56–61,63}		5.34×10^7 ^{39,43,63}	2.27×10^4 ^{39,40,48,64,66}
Operation with CCS	Plant	1.37×10^6 ^{22,29,42,57,59–61}	3.76×10^5	6.07×10^7 ^{22,38,44,45,58}	2.02×10^2 ⁴⁸
Downstream with CCS for EOR	Bio-sequestration	2.13×10^8 ^{10,22,31,32,34,38,39,42–46,53,58,63,78–81,83,96,97}		-3.11×10^8 ^{10,22,31,32,38,39,42–46,53,58,63,78,79,96}	2.84×10^5 ^{10,22,31,32,38,39,42–46,53,58,63,78,79,83,96}
	CO ₂ Conditioning	2.64×10^4 ^{41,79}		1.97×10^6 ^{10,32}	N/A
	Crude Oil Extraction	8.76×10^3 ^{22,34,42,44–46,58,61,78,81,97}		3.51×10^7 ^{22,42,44–46,58}	N/A
	CO ₂ Injection/Recycling	1.57×10^3 ^{22,34,42,44–46,58,61,78,81,97}		3.87×10^6 ^{22,42,44–46,58,78}	N/A
	Crude Oil Transport	1.86×10^4 ^{22,34,42,44–46,58,78,81,97}		1.35×10^6 ^{22,42,44–46,58,78}	N/A
	Crude Oil Refining	1.38×10^6 ^{22,34,42,44–46,58,78,80,81,97}		1.02×10^7 ^{22,42,44–46,58,78}	N/A
	Petroleum Combustion	N/A	4.91×10^5	1.46×10^8 ^{22,42,44–46,58,78}	N/A
	CO ₂ Leakage	N/A		3.53×10^6 ^{31,82,98}	N/A

Table 2. Overview of exergy flow, emissions and land transformation by life cycle phase in a climate neutral coal plant outputting 376 TWhrs and utilizing EOR for an additional output of 491 TWhrs of electricity over the 50 year lifetime, totaling 866 TWhrs. *Carbon sequestration as negative and carbon equivalent emissions as a positive numbers.

location of the PV farm from vegetation clearing and soil respiration³⁸. A key driver of land transformation in the life cycle of PV is the farm itself, transforming 3.94 kha of land^{38,48}.

The exergy input from solar irradiation for bio-sequestration is 12,900 TWhrs. Total GHG emissions to be offset with bio-sequestration are 9.01×10^6 t_{CO₂eq}, transforming 17.2 kha of land^{26,38,49,50}.

Finally, in order to give an accurate comparison of PV to coal with EOR, it is necessary to maintain an equivalent exergy output, so a second scenario with an electrical output of 866 TWhrs over the 50 year lifetime is employed, referred to here as PVs2. All exergy inputs, GHG emissions and land transformation has been scaled up ~2.3 to reflect the larger output. More in depth information on PVs1 and PVs2 can be found in subsequent sections and Tables 3 and 4.

Exergy. The exergy analysis includes the inputs from solar irradiation and the heat content of coal, as well as electricity, diesel and various other sources used to produce electricity with the two methods. With these factored in, the exergy required from solar irradiation for bio-sequestration is orders of magnitude larger than the inputs for the other phases of the life cycle, as shown in Fig. 2a.

For upstream anthropogenic exergy inputs of coal and PV outputting 376 TWhrs, climate neutral coal requires between 92–129 TWhrs more, with a realistic value of 108 TWhrs more (3.24 to 7.45 times more than PVs2 and PVs1, respectively) than climate neutral PV, which results in 36–45 MMTCO₂ with a realistic value of 40 MMTCO_{2eq} more emitted.

Life Cycle Phase	Source/Sink	Exergy _{in} (GWh)	Exergy _{out} (GWh)	Emissions* (t _{CO₂eq})	Land Transformation (ha)
Upstream	Modules	1.25×10^4 ^{49,50,67}		3.47×10^6 ^{38,49,50,67-69}	4.15×10^{248}
	BOS	7.36×10^3 ^{49,50,67}		5.45×10^6 ^{38,49,50,67-69}	1.69×10^{248}
	Construction	7.16×10^1 ^{39,63}		2.52×10^5 ^{39,63}	N/A
	Total	2.00×10^4 ^{39,49,50,63}		8.92×10^6 ^{38,49,50,68,69}	5.84×10^{248}
Operation	Farm	3.50×10^4 ^{37,51,52,70,71,73}	3.76×10^5	8.69×10^4 ³⁸	9.51×10^3 ^{38,48,74-76}
CCS	Bio-Sequestration	1.29×10^7 ^{38,49,50,53,68,69,79,83}		-9.01×10^6 ^{38,49,50,68,69}	1.72×10^4 ^{38,49,50,68,69,83}

Table 3. Overview of exergy flow, emissions and land transformation by life cycle phase in a climate neutral PV farm outputting 376 TWhrs of electricity over the 50 year lifetime. *Carbon sequestration as negative and carbon equivalent emissions as a positive numbers.

Life Cycle Phase	Source/Sink	Exergy _{in} (GWh)	Exergy _{out} (GWh)	Emissions* (t _{CO₂eq})	Land Transformation (ha)
Upstream	Modules	2.89×10^4 ^{49,50,67}		6.62×10^6 ^{38,49,50,67-69}	7.97×10^{248}
	BOS	1.70×10^4 ^{49,50,67}		1.04×10^7 ^{38,49,50,67-69}	3.25×10^{248}
	Construction	1.43×10^2 ^{39,63}		5.81×10^5 ^{39,63}	N/A
	Total	4.60×10^4 ^{39,49,50,63}		1.70×10^7 ^{38,49,50,68,69}	1.12×10^{348}
Operation	Farm	8.05×10^7 ^{37,51,52,70,71,73}	8.66×10^5	2.01×10^6 ³⁸	2.65×10^4 ^{38,48,74-76}
CCS	Bio-sequestration	2.59×10^7 ^{38,49,50,53,68,69,79,83}		-1.72×10^7 ^{38,49,50,68,69}	3.45×10^4 ^{38,49,50,68,69,83}

Table 4. Overview of exergy flow, emissions and land transformation by life cycle phase in a climate neutral PV farm outputting 866 TWhrs of electricity over the 50 year lifetime. *Carbon sequestration as negative and carbon equivalent emissions as a positive numbers.

The additional coal required to offset the energy requirements of the CCS systems necessitates a larger exergy input, 30–38% with a realistic value of 33% more for upstream activities and a range of 31–58% with a realistic value of 38% more coal energy for plant operation. CCS reduces the solar exergy required for bio-sequestration, 2.47–4.69 with a realistic value of 3.16 times less if into a saline aquifer and 1.20–1.25 with a realistic value of 1.22 times less if for EOR than without CCS, illustrated in Fig. 2a and b.

The increased exergy input to upstream and operational phases for coal with CCS is negated by the solar exergy required for bio-sequestration. The error bars represent the minimum and maximum values found in literature for the life cycle phase of each scenario (e.g. these are boundary values not probabilistic estimates). In general, PV has a larger range of values, presumably because of the rapid rate of improvements in technology compared to coal.

GHG Emissions. Over a 50 year lifetime^{36,37}, a photovoltaic farm outputting 376 TWhrs will emit $9.01 \text{ Mt}_{\text{CO}_2\text{eq}} \pm 41.79/7.04 \text{ Mt}_{\text{CO}_2\text{eq}}$ to the atmosphere^{38,49,50}, while coal with CCS into a saline aquifer emits $117.61 \text{ Mt}_{\text{CO}_2\text{eq}} \pm 51.29/49.83$ (over 13x more) and $377.11 \text{ Mt}_{\text{CO}_2\text{eq}} \pm 98.48/58.06 \text{ Mt}_{\text{CO}_2\text{eq}}$ (over 41x more) without CCS, as seen in Fig. 3a^{22,29,36,39,43}. When the coal plant under study utilizes enhanced oil recovery to sequester CO₂ emissions, additional crude oil is produced and is assumed to be combusted for electricity generation, totaling 866 TWhrs. It will emit $310.55 \text{ Mt}_{\text{CO}_2\text{eq}} \pm 72.80/37.31 \text{ Mt}_{\text{CO}_2\text{eq}}$ ^{29,36,39,43}. If the PV farm output is increased to match the net output from the coal plant with EOR, it produces $17.23 \text{ Mt}_{\text{CO}_2\text{eq}} \pm 83.79/13.45 \text{ Mt}_{\text{CO}_2\text{eq}}$ (over 18x less) greenhouse gas emissions, as seen in Fig. 3b^{38,49,50}.

The additional coal required to offset the derating of the plant due to carbon capture technology is made up for by a significant decrease in emissions released to the atmosphere during operation, as seen in Fig. 4a. The leakage of emissions after storage does not greatly affect the total, but there has been little public research on this for large-scale storage. The 2005 IPCC special report provided targets of 0.001%/yr to 0.01% per year. The EPA released regulations in 2011 for CCS leakage mitigation and monitoring stipulating zero leakage^{33,53}, which has prompted companies to report zero leakage and hindered efforts for more accurate studies.

The combustion of refined oil product is less polluting than coal, which helps curtail the downstream emissions, but compared to PVs2 it is still significantly more polluting, as seen in Fig. 4b.

On a per GWh_{out} basis, coal without CCS, coal with CCS into a saline aquifer, coal with CCS for EOR and PV each emit $1004.23 \text{ t}_{\text{CO}_2\text{eq}}/\text{GWh}_{\text{out}}$, $313.17 \text{ t}_{\text{CO}_2\text{eq}}/\text{GWh}_{\text{out}}$, $358.56 \text{ t}_{\text{CO}_2\text{eq}}/\text{GWh}_{\text{out}}$ and $23.99 \text{ t}_{\text{CO}_2\text{eq}}/\text{GWh}_{\text{out}}$, respectively.

Land Transformation. The amount of land transformed by equivalently sized climate-neutral PV electrical power generation is over 13x less than for climate-neutral coal electrical power generation. The use of CCS into a saline aquifer for climate-neutral coal plants helps reduce emissions to the atmosphere and drops it to 5x more than PV, as seen in Fig. 5a. Climate-neutral coal with CCS for EOR also requires 5x more land transformation because the increase in electrical production is offset by the combustion of oil, as seen in Fig. 5b.

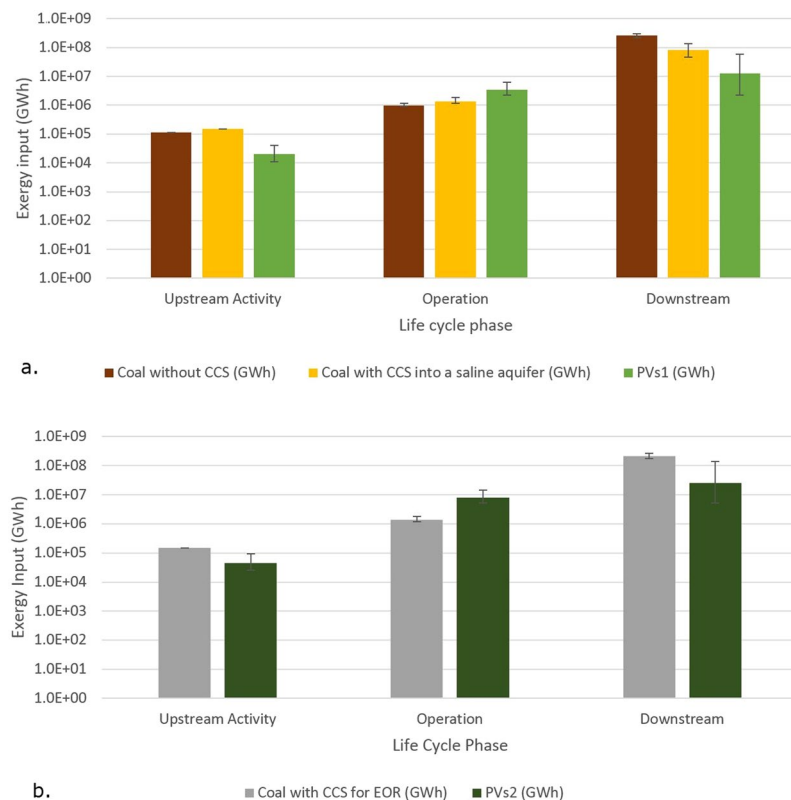


Figure 2. (a) Lifetime exergy input by life cycle phase comparing coal with and without capture into a saline aquifer and photovoltaics, each outputting 376 TWhrs. (b) Lifetime exergy input by life cycle phase comparing climate-neutral coal with EOR and climate-neutral photovoltaic plants, outputting 866 TWhrs. Error bars indicate boundary values.

The majority of land transformation for both PV and coal is for bio-sequestration. For all coal scenarios, 81–95% of the total land transformation is for bio-sequestration, while it is 76% and 78% for PVs1 and PVs2, respectively. For reference, 343 kha of land is transformed in the scenario for a single 1 GW power plant using coal without CCS, which is larger than the state of Rhode Island. If all emissions from coal-fired electricity power generation in the United States were bio-sequestered with switchgrass, it would require 62% of the arable land in the U.S.⁵⁴. With CCS into a saline aquifer, it would still require 20% of the arable land in the U.S. to be planted with switchgrass to bio-sequester the whole fleet⁵⁴.

If the bio-sequestration were left to be performed by the less-efficient average forest in the U.S., then 8.5x more land would be required⁵⁵, resulting in a new forest occupying an area larger than the state of Maryland for a 1GW coal plant without CCS. To bio-sequester the whole fleet of coal plants then a new forest would have to be 2.66 times larger than the existing forest in the U.S., which amounts to 88.54% of the area of the entire U.S.⁵⁴. If CCS into a saline aquifer were utilized, a new forest with an area that is 85.77% of the existing forest in the United States is required⁵⁴. It should be pointed out, however, that land use for biosequestration can have other applications (e.g. forests can be used for wildlife preservation and human recreation) whereas the land area specifically made up for CCS and PV generally can not be used for other applications.

Methods

This section describes in detail the methods used to calculate the exergy, GHG emission and land transformation for coal and PV generation of electricity. When possible, several sources with data on state-of-the-art technology were used and minimum, maximum and average values were determined. The term *realistic* is used to describe the average value or a readily obtained technological value. The equations used to determine the values for exergy, GHG emissions and land transformation for all PV and coal scenarios are stated. SimaPro V8 was utilized and all exergy data is from Cumulative Exergy Demand V1.03 and GHG emissions data is from IPCC GWP 100a. Emissions from the electrical grid are not included in the scope of the LCEAs for PV or coal.

Pre-operation Exergy, Emissions and Land Use for Coal. The total exergy required for mining coal, $\beta_{coalmining}$ for a 1GW power plant over a 50 year lifetime is 6.69×10^4 to 9.21×10^4 GWhrs, without and with CCS, respectively, and is given by:

$$\beta_{coalmining} = \mu_{coalmining} * M_{coal} \text{ [GWhrs]} \quad (1)$$

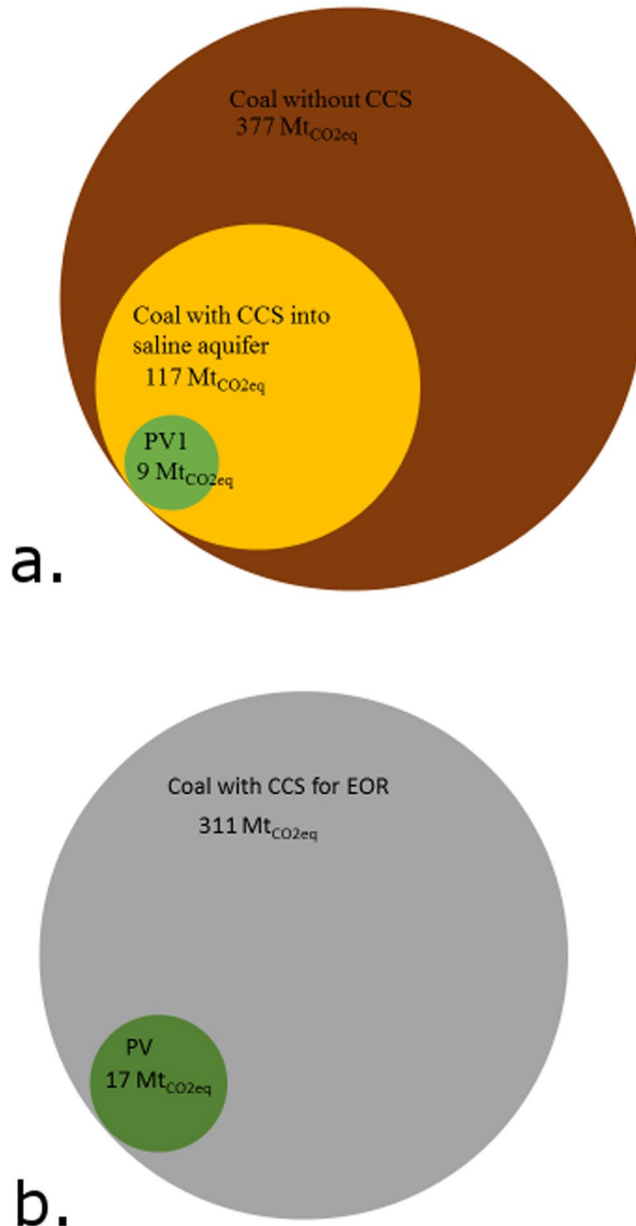


Figure 3. (a) Comparing LCA GHG emissions from a coal plant without carbon capture, a coal plant with saline aquifer CCS, and PVs1 farm. All use bio-sequestration to fully or partially sequester CO₂ and all output 376 TWhrs of electricity. (b) Total LCA GHG emissions from a coal plant with CCS for EOR, and PVs2 farm. Both use bio-sequestration to fully or partially sequester CO₂ and both net output 866 TWhrs of electricity over their lifetime.

where,

$$M_{coal} = \frac{\beta_{out}}{\eta_{coalplant} * \epsilon_{coal}} \quad [t] \tag{2}$$

where β is the exergy in GWhrs, μ is the specific exergy in GWh/t_{coal}, M_{coal} is the total amount of coal required for combustion over the lifetime in tons, β_{out} is the desired electrical output of the plant over its lifetime in GWhrs, η is efficiency and ϵ is the heat content of coal in GWh/ton.

The specific mining exergy for coal is 4.40×10^{-4} GWh_{in}/t_{coal}³⁹ and the average heat content of coal consumed by electrical power plants in the U.S. is 6.54×10^{-3} GWh/ton⁵⁶. The amount of coal required for the 1GW power plant without carbon capture technology during its lifetime ranges from 1.41×10^8 – 1.77×10^8 tons, with a realistic value of 1.52×10^8 tons^{22,29,36,42,56–59} and with carbon capture it ranges from 1.85×10^8 – 2.80×10^8 tons with a realistic value of 2.10×10^8 tons^{22,29,42,56–61}. The efficiency of the plant drives the required exergy input and

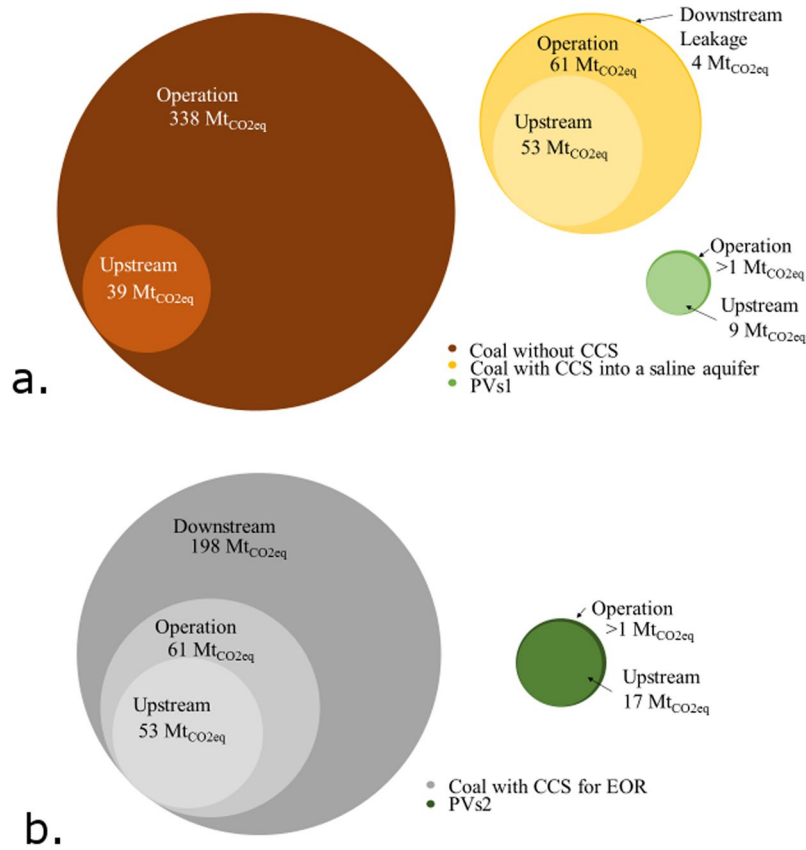


Figure 4. (a) To-scale visualization of GHG emissions by life cycle phase for coal without CCS, coal with CCS into a saline aquifer and PV, each outputting 376 TWhrs of electricity over their lifetimes. (b) To-scale visualization of GHG emissions by life cycle phase for, coal with CCS for EOR and PV, each outputting 866 TWhrs of electricity over their lifetimes.

a review of the literature has found it to range from 32.50–40.60% with an average of 37.74% without carbon capture technology and 20.90–31.51% with an average of 27.40% with carbon capture technology^{22,36,42,56,59,60,62}.

The total exergy required for transporting coal for a 1GW power plant over the 50 year lifetime, $\beta_{coaltransport}$ is 3.17×10^4 and 4.37×10^4 GWhrs without and with CCS, respectively, and is given by:

$$\beta_{coaltransport} = \frac{\mu_{coaltransport,rail} + \mu_{coaltransport,marine} + \mu_{coaltransport,truck} * M_{coal}}{\beta_{coaltransport}} \text{ [GWhrs]} \tag{3}$$

where,

$$\mu = \vartheta * \varphi \text{ [GWh/t}_{coal}] \tag{4}$$

where ϑ is the specific exergy in GWh/ton-km and φ is the specific distance in ton-km/t_{coal}. Coal is transported for electrical generation via three main modes, rail, marine and truck, which account for 88%, 11% and 1%, respectively by ton-km³⁹. Trains transport 1.04 ton-km/kg_{coal} at 1.81×10^{-7} GWh/ton-km, marine transports 130 ton-km/t_{coal} at 1.36×10^{-7} GWh/ton-km and trucks transport 10 ton-km/t_{coal} at 3.46×10^{-7} GWh/ton-km³⁹.

The exergy required for construction, $\beta_{coalconstruction}$, is 1.29×10^4 GWhrs for a plant with and without CCS (the procurement of the additional equipment for compressing the CO₂ is assumed to be negligible) and is calculated by:

$$\beta_{coalconstruction} = \Sigma(M_{coalmaterials} * \mu_{coalmaterials}) \text{ [GWh]} \tag{5}$$

where $M_{coalmaterials}$ is the tonnage of individual materials⁶³ and $\mu_{coalmaterials}$ is the specific exergy of the materials in GWh/t³⁹. Total construction exergy is 9.4% of the total exergy required by upstream activities, detailed in Table 5.

Total upstream greenhouse gas emissions for a 1GW coal plant, $\pi_{coalupstream}$ are 3.92×10^7 and 5.34×10^7 t_{CO2eq} without and with CCS, respectively and are given by:

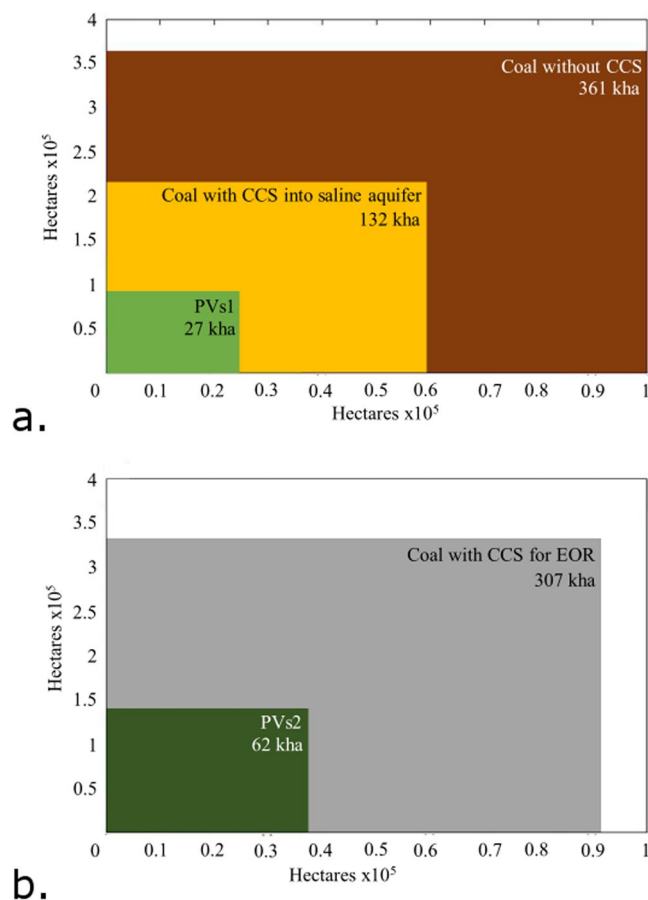


Figure 5. (a) Land transformation shown to scale in hectares for bio-sequestration required to provide for climate-neutral coal without CCS, coal with CCS into a saline aquifer and PV, each producing 376 TWhrs electricity over their lifetime. (b) Land transformation shown to scale in hectares for bio-sequestration required to provide for climate-neutral coal with CCS for EOR and PV, both producing 866 TWhrs electricity over their lifetime.

	Material	Mass (tons) ⁶³	Specific Exergy Input (GJ/ton) ³⁹	Exergy Input (GWh) ^{39,63}
Coal Plant	Steel	6.22×10^4	3.20	5.57×10^1
	Aluminum	6.24×10^2	3.87×10^1	6.76
	Concrete	1.78×10^5	8.16×10^{-1}	4.07×10^1
	Electricity	N/A	N/A	1.27×10^4
	Oil	7.09×10^2	4.08×10^1	8.09
	Coal	1.43×10^4	6.83×10^{-6}	9.80×10^1
	Total	2.56×10^5		1.29×10^4
PV Farm	Steel	1.04×10^3	3.20	9.26×10^{-1}
	Aluminum	4.00×10^1	1.63×10^2	1.82
	Concrete	5.00×10^2	1.07	1.50×10^{-1}
	Silicone	5.00×10^1	5.71×10^3	7.99×10^1
	Glass	2.40×10^2	1.71×10^1	1.15
	Copper	1.08×10^2	N/A	N/A
	Insulator	9.20×10^1	N/A	N/A
	Electricity	N/A	N/A	1.70
	Oil	9.70×10^1	4.08×10^1	1.11
	Coal	2.90×10^1	6.83×10^{-6}	5.55×10^{-8}
	Total	2.19×10^3		8.68×10^1

Table 5. Construction exergy for large scale PV and coal electricity generation, each outputting 376 TWhrs over a 50 year lifetime.

Material	Mass (ton) ⁶³	Specific Emissions (t _{CO₂eq} /ton) ³⁹	Emissions (t _{CO₂eq}) ^{39,63}
Steel	1.04 × 10 ³	2.25 × 10 ²	2.33 × 10 ⁵
Aluminum	4.00 × 10 ¹	8.80	3.52 × 10 ²
Concrete	5.00 × 10 ²	1.28 × 10 ⁻¹	6.38 × 10 ¹
Silicone	5.00 × 10 ¹	3.30 × 10 ²	1.65 × 10 ⁴
Glass	2.40 × 10 ²	1.34	3.22 × 10 ²
Insulator	9.20 × 10 ¹	N/A	N/A
Copper	1.08 × 10 ²	N/A	N/A
Electricity	N/A	N/A	1.38 × 10 ³
Oil	9.70 × 10 ¹	3.88	3.77 × 10 ²
Coal	2.90 × 10 ¹	1.60	4.64 × 10 ¹
Total GHG Emissions	2.19 × 10 ³		2.52 × 10 ⁵

Table 6. GHG emission for the construction of a PV farm outputting 376 TWhrs over a 50 year lifetime.

$$\pi_{coalupstream} = \left((\alpha_{coalmining} * \epsilon_{coalmining}) + (\alpha_{coaltransport} * \epsilon_{coaltransport}) \right) * M_{coal} + (\alpha_{coalconstruction} * \beta_{yearlyoutput}) [t_{CO_2eq}] \quad (6)$$

where α is the specific emissions in t_{CO₂eq}/t_{coal}, ϵ is the percent contribution and $\beta_{yearlyoutput}$ is the exergy output per year from the operation phase (not including any downstream processes). The highest individual contributions come from mining and transportation. Specifically, mining emits 0.23 t_{CO₂eq}/t_{coal} (55% of total) and transport emits 0.19 t_{CO₂eq}/t_{coal} (45% of total), which totals 0.41 t_{CO₂eq}/t_{coal}³⁹. Furthermore, total upstream emissions are 55 t_{CO₂eq}/GWh_{out}, resulting in 0.12 t_{CO₂eq}/t_{coal}⁴³. The average of these two values provides a total upstream emission factor of 0.27 t_{CO₂eq}/t_{coal}. The yearly output is simply the lifetime output divided by 50, which is 7.5 TWhr/yr when the lifetime output is 376 TWhrs and 17.3 TWh/yr when the lifetime output is 866 TWhrs.

Construction of a large coal power plant emits 0.022 kg_{CO₂eq}/kWh-yr⁶³, resulting in less than 1% of the total upstream emissions for the plant under study. More detailed information is provided in Table 6.

Mining emissions for the 1GW plant over its lifetime range from 1.14 × 10⁷–4.74 × 10⁷ t_{CO₂eq} with a realistic value of 2.94 × 10⁷ t_{CO₂eq} and 8.74 × 10⁶–3.44 × 10⁷ t_{CO₂eq} with a realistic value of 2.16 × 10⁷ t_{CO₂eq} for a plant with and without capture, respectively^{39,43}.

Transport emissions for the 1GW plant over its lifetime range from 9.30 × 10⁶–3.88 × 10⁷ t_{CO₂eq} with a realistic value of 2.4 × 10⁷ t_{CO₂eq} and 7.15 × 10⁶–2.81 × 10⁷ t_{CO₂eq} with a realistic value of 1.76 × 10⁷ t_{CO₂eq} for a plant with and without capture, respectively^{39,43}.

Land transformation for upstream activities for a 1GW coal plant, $A_{coalupstream}$, are 17.8 kha and 22.7 kha without and with CCS, respectively and calculated by:

$$A_{coalupstream} = (\tau_{coalmining} + \tau_{coaltransport}) * \beta_{out} [kha] \quad (7)$$

where τ_{coal} is the specific land transformation in ha/t_{coal}. In the U.S., there are 195 kha of land leased for coal mining, but only 140 kha of the land actively being used⁶⁴ with 8.97 × 10⁸ tons of coal mined each year⁴⁰ giving an average of 1.52 × 10⁻⁴ ha/t_{coal}. Surface mining transforms 90–1,820 m²/kt with a realistic value of 300 m²/kt and underground mining transforms 4.5–1,110 m²/kt with a realistic of 30 m²/kton⁴⁸. Given that on average 70% of the coal mined in the U.S. is from surface mining and 30% from underground mining⁴⁸, the average of these various values was taken to provide a realistic value of 8.70 × 10⁻⁵ ha/t_{coal}.

Specific land transformed by rail infrastructure ranges from 30 m²/GWh in the east to 80 m²/GWh in the west⁴⁸. Given that 88% of coal shipped to electrical power plants is by rail⁶⁵ and another 11% by water³⁹ it is assumed the land transformed by rail is representative of the total land transformation. 55% of the coal is mined in the west and 45% in the east⁶⁶ so a realistic value was assumed to be 5.75 × 10⁻³ ha/GWh. When multiplied by the ratio of β_{out} over t_{coal} consumed by the plant with and without carbon capture over its lifetime it equates to 1.42 × 10⁻⁵ ha/t_{coal} and 1.03 × 10⁻⁵ ha/t_{coal}, respectively. Each range from 1.22 × 10⁻⁵–1.53 × 10⁻⁵ ha/t_{coal} and 7.72 × 10⁻⁶–1.17 × 10⁻⁵ ha/t_{coal}, respectively.

The land transformed by the upstream activities for the construction of the coal power plant is not included in the scope of this analysis rendering all values for coal conservative over the entire life cycle.

Pre-operation Exergy, Emissions and Land Use for PV. The exergy required for upstream activities, $\beta_{PVupstream}$, is 2.00 × 10⁴ GWhrs for PVs1 and 4.60 × 10⁴ GWhrs for PVs2 and is calculated by:

$$\beta_{PVupstream} = (\dot{t}_{EPB} * \beta_{yearlyoutput}) + \beta_{PVconstruction} [GWhrs] \quad (8)$$

where \dot{t}_{EPB} is the energy payback time in years, which ranges from 1.7–5.5 years, with an average of 2.7 years^{49,50}. This was multiplied by the yearly output to determine the upstream exergy input of 5.3 × 10⁻² GWh_{in}/GWh_{out}.

Efficiencies	Min (%)	Max (%)	Realistic (%)
MEA	26.24 ⁴¹	29.90 ⁵⁷	28.03 ^{22,29,41,42,57}
Membrane*	27.23 ⁶⁰	31.67 ⁵⁹	29.77 ^{59,60,99}
Ammonia			27.90 ⁴²
Other	20.90 ²⁹	33.36 ²⁹	26.77 ²⁹

Table 7. Range of pulverized coal plant efficiencies equipped with various forms of carbon capture.

*Membranes are either 2-stage or 2-stage with a 1 or 2 stage air sweep.

Individually, the energy contribution from the modules and BOS are 63% and 37% of the total, respectively⁶⁷. The construction exergy was calculated by multiplying the tonnage of material by the upstream exergy for each material^{39,63}, more detailed data is provided in Table 5.

The upstream GHG emissions, $\pi_{PVupstream}$, are 8.92×10^6 t_{CO₂eq} and 1.70×10^7 t_{CO₂eq} for PVs1 and PVs2, respectively and is calculated with:

$$\pi_{PVupstream} = \left(\frac{\alpha_{PVupstream} * \beta_{out}}{2} \right) + \pi_{PVconstruction} \quad [t_{CO_2eq}] \quad (9)$$

where α_{PV} is the specific GHG emissions in t_{CO₂eq}/GWh_{out} in its life cycle, which range from 8.74–187 t_{CO₂eq}/GWh_{out}, with a realistic value of 46.98 t_{CO₂eq}/GWh_{out}^{38,49,50,68,69}. The individual contributions of modules and BOS to total emissions are 38.9% and 61.1%, respectively⁶⁷. The emissions from construction are detailed in Table 6. LCAs typically assumed a lifetime of 20–30 years. The values given in this paper assume that a negligible amount of greenhouse gases are emitted and after 25 years of operation, and a negligible amount of GHG's are emitted.

Land transformation from upstream activities, $A_{PVupstream}$, are 0.58 kha and 1.12 kha for PVs1 and PVs2, respectively and is calculated with:

$$A_{PVupstream} = \frac{(\tau_{PVmodules} + \tau_{PVBOS}) * \beta_{out}}{2} \quad [kha] \quad (10)$$

where τ_{PV} is the specific land transformation in ha/GWh_{out}. Land transformation for upstream activity is 1.84×10^{-3} ha/GWh_{out} and 7.5×10^{-4} ha/GWh_{out} for modules and BOS, respectively⁴⁸. The upstream land transformation for materials and processes specific to construction of the PV farm were not included so total values can be considered conservative.

Operation Exergy, Emissions and Land Use for Coal. The exergy into the coal plant during operation is comprised entirely from the latent energy in the coal. The exergy inputs required, $\beta_{coaloperation}$, are 9.95×10^5 and 1.37×10^6 GWhrs without and with CCS, respectively and are calculated by:

$$\beta_{coaloperation} = \frac{\beta_{out}}{\eta_{plant}} \quad [GWhrs] \quad (11)$$

The efficiency of a state-of-the-art plant without CCS ranges from 32.5–40.6% with a realistic value of 37.74%, requiring an input range from 9.25×10^5 – 1.16×10^6 GWh with a realistic value of 9.95×10^5 GWh^{22,29,36,42,57,60,62}. With various forms of CCS, the efficiency ranges from 20.90–31.51% with a realistic value of 27.4% requiring an exergy input range from 1.21×10^6 – 1.83×10^6 GWh with a realistic value of 1.637×10^6 GWh^{22,29,42,57,59–61}. Thus, carbon capture technology necessitates 37.74% more coal, which creates additional GHG emissions. The realistic capture in this study is taken as 82.2%.

The carbon capture efficiency ranges from 81–91% capture of total emissions^{22,29,41,42,57,59–61}. The most common and technologically mature method of carbon capture at the plant is post-combustion capture using MEA. Several other carbon capture processes were included in the purview of the study and are shown in Table 7. The efficiency drop due to CCS comes from the high energy intensity of the carbon capture process. Large-scale MEA processes can consume 92–119 MW_{el} and an additional 0.72–1.74 MW_{th}/MW_{eloutput}. This results in an average of 0.11 GW_{el} and 0.99 GW_{th} for a ~1GW power plant⁴¹. These values are conservative because the carbon capture percentage in the study was 60–65%. The average energy efficiency of a state of the art coal plant in the U.S. is used after having identified the energy efficiency for the top 10% of the fleet³⁶.

The GHG emissions to the atmosphere during operation, $\pi_{coaloperation}$, are 3.38×10^8 and 6.07×10^7 t_{CO₂eq} without and with CCS, respectively and are calculated by:

$$\pi_{coaloperation} = \alpha_{coaloperation} * \beta_{out} \quad [t_{CO_2eq}] \quad (12)$$

where the specific GHG emissions from coal plants without carbon capture range from 807–1100 t_{CO₂eq}/GWh, with a realistic value of 900 t_{CO₂eq}/GWh^{38,44,45,58}. Emissions from plants with capture range from 124–203 t_{CO₂eq}/GWh, with a realistic value of 160 t_{CO₂eq}/GWh^{22,44,45,58}.

Land transformation caused by the plant itself, $A_{coaloperation}$, is 202 ha and calculated by:

$$A_{coaloperation} = \tau_{coaloperation} * \beta_{out} \text{ [kha]} \quad (13)$$

where the specific land transformation ranges from 6.0×10^{-4} – 3.3×10^{-3} ha/GWh_{out}, with an average of 9.0×10^{-4} ha/GWh_{out}⁴⁸.

Operation Exergy, Emissions and Land Use for PV. In the operation phase, the solar irradiation accounts for the entirety of the exergy input, $\beta_{PVoperation}$, totaling 3.50×10^6 and 8.05×10^6 GWhrs for PVs1 and PVs2, respectively and is calculated by:

$$\beta_{PVoperation} = \Sigma \left(\frac{\beta_{yearlyoutput}}{\eta_{PVyearly}} \right) \text{ [GWhrs]} \quad (14)$$

where,

$$\eta_{PVyearly} = \eta_0 * (1 - d)^n \text{ [%]} \quad (15)$$

where η_0 is the initial exergy efficiency of the PV system, d is the degradation rate in %/yr and n is the years of operation. The exergetic efficiency of PV was found to range from 7.8–16.1%, with a realistic value being 12.1%^{51,52,70–72}. The degradation rate ranged from 0.35–0.8%/yr with a realistic average of 0.49%/yr^{37,73}. System Advisor Model (SAM) from the National Renewable Energy Laboratory (NREL) was employed to ensure the accuracy of values from the calculations above⁷⁴.

The GHG emissions released to the atmosphere during operation, $\pi_{PVoperation}$, are 8.69×10^4 and 2.01×10^5 tCO₂eq for PVs1 and PVs2, respectively, and calculated by:

$$\pi_{PVoperation} = \frac{\alpha_{PVoperation} * \beta_{out}}{2} \text{ [tCO}_2\text{eq]} \quad (16)$$

A range of 0–46.3 tCO₂eq/GWh_{out}³⁸ are emitted during installation of a PV farm. The worst case assumes locating a PV farm in a heavily forested area with CO₂ emissions from loss of forest sequestration, soil respiration and oxidation of cut biomass. An assumption of 0.46 tCO₂/GWh (1%) from deforestation was employed for this study as forests are not typically clear cut for PV farms.

Land transformation due to the PV farm, $A_{PVoperation}$, is 3.94 and 9.51 kha and 9.22 and 26.46 kha for PVs1 and PVs2, respectively and are calculated as the average of two approaches:

$$A_{PVoperation} = \tau_{PVoperation} * C_{NP} \text{ [kha]} \quad (17)$$

$$A_{PVoperation} = \tau_{PVoperation} * \beta_{out} \text{ [kha]} \quad (18)$$

where τ_{PV} is the specific land transformation in ha/GW and C_{NP} is the nameplate capacity. The PV farms themselves ranges from 2.02–3.23 kha/GW³⁸, while a review of three of the largest PV farms in the United States (Solar Star, Mount Signal and California Valley) reveals that they are 2.25, 3.89 and 5.20 kha/GW, respectively, giving an average of 3.32 kha/GW^{75–77}. Land transformation for the modules and BOS combined range from 1.64×10^{-2} ha/GWh_{out} to 4.62×10^{-2} ha/GWh_{out}, with a realistic value of 3.59×10^{-2} ha/GWh_{out}⁴⁸. These were multiplied by nameplate capacity or lifetime exergy output and then averaged together to determine the final values. It should be noted here that the PV farms are best suited from an environmental standpoint or barren land or existing man-made structures (e.g. rooftops, sound barriers, parking lot awnings, etc.) and should be used before fertile land is used because of the negative impacts on food price and availability.

Downstream Exergy, Emissions and Land Use for Coal. The exergy input from solar irradiation for bio-sequestration of GHG emission from coal without CCS, $\beta_{coalbio}$, is 2.57×10^8 GWhrs and calculated by:

$$\beta_{coalbio} = G * N * A_{coalbio} \text{ [GWhrs]} \quad (19)$$

where G is the average U.S. solar incidence of 15,000 GWh/ha * yr⁷⁸, N is the number of years over its lifetime and $A_{coalbio}$ is the land transformation required by the switchgrass for upstream and operation activities without CCS in hectares, explained in equation 32 below.

The exergy input for bio-sequestration of GHG emissions from coal with CCS into a saline aquifer, $\beta_{coalCCS}$, is 8.14×10^7 GWhrs and calculated with:

$$\beta_{coalCCS} = \beta_{coalCCSbio} + \beta_{CO_2cond} \text{ [GWhrs]} \quad (20)$$

$$\beta_{coalCCSbio} = G * N * A_{coalCCSbio} \text{ [GWhrs]} \quad (21)$$

$$\beta_{CO_2cond} = \mu_{CO_2cond} * \gamma \text{ [GWhrs]} \quad (22)$$

where $A_{coalCCSbio}$ is the land transformation required by the switchgrass for upstream, operation and downstream activities with CCS into a saline aquifer in hectares explained in equation 33 below, μ_{CO_2cond} is the specific exergy

required to condition the CO₂ (compress and transport) after its been separated and measured in GWh/t_{CO₂}, and γ is the total CO₂ captured in t_{CO₂}. CO₂ is typically transported via pipeline in a supercritical state, between 8.6–15.3 MPa⁴³. The specific energy required to compress CO₂ is between 112–119 kWh/t_{CO₂}, realistically being 116 kWh/t_{CO₂}^{41,78}. The pipelines have been found to lose between 4–50 kPa per 100 km⁷⁹, thus requiring 6.5 kWh/t_{CO₂} to boost the pressure for longer transport⁴³ but the assumption in this study is that no pressure boosters are required. The average distance for CO₂ to travel for sequestration purposes is 190.5 km³² and the Weyburn case demonstrates that CO₂ can be transported 330 km without additional boosting energy⁷⁸. The total CO_{2,eq} captured is the difference between GHG emissions from a coal without CCS and a coal plant with CCS, which are 3.38×10^8 t_{CO_{2,eq}} and 6.02×10^7 t_{CO_{2,eq}} respectively.

The exergy input for bio-sequestration of GHG emission from coal with CCS for EOR, $\beta_{coalEOR}$, is 2.13×10^8 GWhrs and calculated with:

$$\beta_{coalEOR} = \beta_{coalbio} + \beta_{coalCCSbio} + \beta_{oil extraction} + \beta_{oil transport} + \beta_{oil refine} \quad [\text{GWhrs}] \quad (23)$$

where,

$$\beta_{oil extraction} = \mu_{oil extract} * M_{oil} \quad [\text{GWhrs}] \quad (24)$$

$$\beta_{oil transport} = \mu_{oil transport} * M_{oil} * D_{oil} \quad [\text{GWhrs}] \quad (25)$$

$$\beta_{oil refine} = M_{oil} * (1 - \eta_{refinery}) * \epsilon_{oil} \quad [\text{GWhrs}] \quad (26)$$

where,

$$M_{oil} = \gamma * \theta_{oil} \quad [\text{t}] \quad (27)$$

and where $\mu_{oil extract}$ is the specific exergy required to pump the oil from the reservoir in GWh/t_{oil}, M_{oil} is the amount of additional oil extracted with the EOR process in t_{oil}, $\mu_{oil transport}$ is the specific exergy to transport the oil to the refinery in GWh/ton-km_{oil}, D_{oil} is the average distance oil travels to the refinery in km, $\eta_{refinery}$ is the efficiency of the refinery, ϵ_{oil} is the energy content of crude oil and θ_{oil} is the specific oil production from the EOR process in t_{oil}/t_{CO₂}.

For enhanced oil recovery, it takes 4.40×10^{-5} – 1.38×10^{-4} GWh/t_{oil}, with a realistic value of 7.40×10^{-5} GWh/t_{oil} to extract crude oil^{61,80}. The exergy required for recycling and re-injecting the CO₂ continuously ranges between 3.21–9.00 kWh/t_{CO₂ injected}, with a realistic value of 6.10 kWh/t_{CO₂ injected}^{43,80}. The exergy required for recycling the CO₂ is captured under the extraction exergy.

An additional exergetic input of 8.15×10^8 GWh/t_{oil} is needed to transport it to a refinery and the average distance crude oil travels to a refinery is 1200 km⁴³.

A typical refinery operates at 90.1% efficiency⁸⁰ and approximately 93% of this turns into combustible products⁴³. The crude oil was assumed to have a heat content of 1.17×10^{-2} GWh/ton⁷⁸ and all the refined product to have a heat content of 1.14×10^{-2} GWh/ton³⁹. The exergy required to transport the refined product is considered negligible⁴³.

The specific tonnage of oil produced from EOR ranges from 0.18 to 0.89 t_{oil}/t_{CO₂ injected} with an average of 0.43 t_{oil}/t_{CO₂ injected}^{34,46,80–82}.

Equations 28–32 calculate the GHG emissions of coal without CCS, $\pi_{coalbio}$, coal with CCS into a saline aquifer, $\pi_{coalCCS}$, and coal with CCS for EOR, $\pi_{coalEOR}$, which are 3.77×10^8 , 1.18×10^8 and 3.11×10^8 t_{CO_{2,eq}}, respectively.

$$\pi_{coalbio} = \pi_{coalupstream} + \pi_{coaloperation} \quad [\text{t}_{\text{CO}_2\text{eq}}] \quad (28)$$

$$\pi_{coalCCS} = \pi_{coalupstream} + (\pi_{coaloperation} * (1 - \gamma)) + \pi_{leak} \quad [\text{t}_{\text{CO}_2\text{eq}}] \quad (29)$$

$$\pi_{coalEOR} = \pi_{coalCCS} + \pi_{EOR} \quad [\text{t}_{\text{CO}_2\text{eq}}] \quad (30)$$

where,

$$\pi_{leak} = \frac{\rho_{reservoir} * N * \gamma}{\alpha_{CO_2 transport} * D_{CO_2}} \quad [\text{t}_{\text{CO}_2\text{eq}}] \quad (31)$$

$$\pi_{EOR} = [(\rho_{extraction}) + [(\theta_{transport} + \theta_{refine} + \theta_{combust}) * \epsilon_{oil}]] * \gamma \quad [\text{t}_{\text{CO}_2\text{eq}}] \quad (32)$$

where $\rho_{reservoir}$ is the leakage rate from the oil and gas reservoir in %/yr, $\alpha_{CO_2 transport}$ is the specific emissions from the pipeline transport of CO₂ in t_{CO₂}/km, D_{CO_2} is the distance CO₂ travels in the pipe from the plant to the reservoir in km, $\rho_{extraction}$ is the CO₂ released to the atmosphere during the recycling and re-injection and θ is the specific emissions in t_{CO₂}/bbl, where bbl is short for a barrel of oil and 7.33 bbl equate to one metric ton of crude oil.

Biomass Type	Value (tC/ha * yr)
Switchgrass	6.0 ⁸⁴
Poplar	5.4 ⁸⁴
Willow	4.3 ⁸⁴
Woody Tissue	3.8 ²⁵
Average US Forest	0.7 ²⁶

Table 8. Carbon uptake rates of various types of biomass.

The downstream processes of EOR emit significant amounts of greenhouse gas. Separating and recycling the CO₂ for re-injection is important to curtail emissions during EOR. Alternating floods of water and CO₂ gas are injected into oil deposits to increase oil production. For EOR optimized for carbon sequestration, it can take months for the CO₂ to start being extracted with the crude oil and will continue to be extracted for years after flooding has stopped⁴⁶. During crude oil extraction, 13.7% of the total injected CO_{2eq} is lost to the atmosphere when assuming that CO₂ is injected for 10 years and then recycled for another 10 years. 11% of these losses come from recycling, 38% from venting CO₂ and 42% from venting CH₄⁴⁶. Transport of crude oil to the refinery emits 4×10^{-3} t_{CO_{2eq}}/bbl, refining the crude emits 3×10^{-2} t_{CO_{2eq}}/bbl and combusting the refined product emits 0.43 t_{CO_{2eq}}/bbl⁴⁶. The energy content of crude oil is 41.9 GJ/ton⁸⁰. Transportation of the refined product is considered negligible⁴³.

The target for leakage from geological storage, like that used in saline aquifers and EOR, should be between 1×10^{-2} – 1×10^{-1} %/yr or 1×10^{-3} – 1×10^{-2} %/yr^{31,83}, so a realistic value of 2.75×10^{-2} %/yr is used. There are over 4,500 km of CO₂ pipelines⁸³ which emit 4.64×10^7 t_{CO_{2eq}} each year¹⁰, resulting in emissions of 1.03×10^4 t_{CO_{2eq}}/km and the average distance the CO₂ is pumped is 190.5 km³².

The land transformation required for bio-sequestration for coal without CCS, $A_{coalbio}$, coal with CCS into a saline aquifer, $A_{coalCCS}$, and coal with CCS for EOR, $A_{coalEOR}$, is 343, 109 and 284 kha, respectively and calculated using:

$$A_{coalbio} = \frac{\pi_{coalbio} * \sigma}{\omega * N} \text{ [kha]} \quad (33)$$

$$A_{coalCCS} = \frac{(\pi_{coalbio} + \pi_{leak}) * \sigma}{\omega * N} \text{ [kha]} \quad (34)$$

$$A_{coalEOR} = \frac{(\pi_{coalbio} + \pi_{leak} + \pi_{EOR}) * \sigma}{\omega * N} \text{ [kha]} \quad (35)$$

where σ is the molar ratio of carbon to CO₂, which is $\left(\frac{12}{44}\right)$ and ω is the rate of carbon uptake by switchgrass, which is 6 t_C/ha-yr⁸⁴. The scenario without CCS does not have any GHG emissions from leakage or EOR and the scenario with CCS into a saline aquifer does not have any GHG emissions from EOR. The pipelines used to transport CO₂ are considered to be buried and hence have a negligible amount of land transformation.

Downstream Exergy, Emissions and Land Use for PV. Solar incidence on the land required for sequestration accounts for the total exergy into this phase of the analysis. The exergy inputs, β_{PVbio} , are 1.29×10^7 and 2.59×10^7 GWh for PVs1 and PVs2, respectively are calculated with:

$$\beta_{PVbio} = G * N * A_{PVbio} \text{ [GWhrs]} \quad (36)$$

where,

$$A_{PVbio} = \frac{(\alpha_{PVupstream} + \alpha_{PVoperation}) * \beta_{yearlyoutput} * \sigma}{\omega} \text{ [kha]} \quad (37)$$

Switchgrass offers the best carbon sequestration potential of 6 t_C/ha-yr⁸⁴ and is assumed to sequester the CO_{2eq} released by the implementation of the PV farm. The sequestration potentials of various biomass can be seen in Table 8. It has been shown to sequester steadily for over 50 years with little maintenance⁸⁵.

The total emissions from PV to be sequestered by biomass, π_{PVbio} , are 9.01×10^6 and 1.72×10^7 t_{CO_{2eq}} for PVs1 and PVs2 respectively, over the 50 year lifetime and are calculated by:

$$\pi_{PVbio} = \pi_{upstream} + \pi_{operation} \text{ [t}_{CO_2eq}\text{]} \quad (38)$$

It should be noted that the values for PV can be improved further in the future as widespread PV recycling becomes widespread^{86,87}. To date the vast majority of PV is still operational, however, in the future recycling of PV will become significantly more important. Advanced recycling can reduce the embodied energy of PV on the manufacturing end by enabling industrial symbiosis^{88–90}. This transfer to waste products back into the wealth created by PV electricity generation can directly benefit the circular economy⁹¹.

Lastly, it should be pointed out that all more efficient dual uses of land were not considered (e.g. mounting PV on the rooftops of CCS facilities or using the surface area in-between rows of PV for agricultural farming (agrivoltaics^{92–95}).

Conclusions

The growth and maturation of photovoltaic technology has enabled it to provide large-scale electricity generation and supplant existing large-scale coal generation. Both solar and coal technologies have the capacity to be climate neutral using bio-sequestration and CCS. The additional land area required to bio-sequester coal-fired electricity in the U.S. is physically impossible in some cases and not realistic in the best case, where CCS and EOR do improve coal performance. Even with the best available technologies the use of coal to provide climate-neutral power cannot be justified because the potential for far more effective use of land with PV. This study showed that solar photovoltaic technology is a far superior use of land for climate neutral electricity generation than any technology coupled to coal.

Recent advances have made CCS more feasible, and in conjunction with EOR more practical. However, the process of EOR only sequesters 28% of the CO₂ injected due to subsequent downstream emissions. But, when comparing coal emissions on a per GWh_{electric output} basis, a plant with CCS for EOR is only slightly worse to a plant with CCS into saline aquifers. Largely because the combustion of oil is less polluting than the combustion of coal, which mitigates its inherent emissions.

The results of this study have shown that CCS is unable to make climate-neutral coal competitive with climate-neutral PV in average solar conditions. Climate-neutral photovoltaic farms are a better option than climate neutral coal from an exergy, GHG emissions and land transformation perspective, by several orders of magnitude each. Future work is needed to carefully consider the cost benefit analysis of policies to support climate-neutral electricity generation. Research and policy promoting rapid deployment in photovoltaic technology offers more promising solutions to combat climate change than continued research into advanced coal and CCS.

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Author Contributions

J.G.G. performed the data collection and analysis. J.M.P. conceived of the study and assisted in analysis. All authors wrote the manuscript.

Additional Information

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