MASTER THESIS

ENERGY TECHNOLOGY FOR SUSTAINABLE DEVELOPENT

Optimized GHG Emissions and Land Transformation for Climate Neutral Electricity Production: Coal with Carbon Capture and Sequestration vs Solar Photovoltaic

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ABSTRACT

Negative effects of climate destabilization caused by greenhouse gas (GHG) emissions are caused in large part by electricity power generation. Climate neutral power generation will impede the increase in global temperatures. Coal-fired power plants can implement carbon capture and sequestration (CCS) to capture and/or offset the release of GHG's to the atmosphere. Whereas, solar photovoltaic (PV) technology primarily emits GHGs during extraction and fabrication and has near zero GHG emissions during operation. To determine preferred approaches to climate-neutral electricity generation, life cycle analysis studies for energy, GHG emissions and land transformation for climate-neutral electricity were aggregated and synthesized.

Over the full life cycle, coal plants emit over 41 times more GHG's than a PV system with the same electrical output under average insolation. The addition of CCS systems to coal plants still emits 13 times more GHG. State-of-the-art carbon capture systems typically capture 90% of the CO_2 produced, so some form of sequestration using biomass, referred to here as bio-sequestration, is required to be truly climate neutral. For PV systems, bio-sequestration alone is modeled to make it climate neutral. This results in coal plants without CCS and with CCS transforming 16 times and 5 time more land than PV. If the CO_2 is utilized for enhanced oil recovery (EOR) and the additional oil production is combusted for electricity generation, it will only sequester 27% of the CO_2 injected, over its life cycle. Emitting 18 times more GHG's and transforming 7 times more land than an equivalently sized PV system.

For comparison, optimal bio-sequestration of all coal-fired GHG's released to the atmosphere in the U.S requires 67% of arable land in the United States (U.S.). Even with CCS, coal fired electricity generation would still require 21% of all arable land in the U.S and 55% if CO_2 is utilized for EOR.

Keywords: CCS, Carbon Capture and Sequestration, PV, Photovoltaic, Climate Neutral Electricity Generation, GHG, Greenhouse Gas, emissions, CO2, Land Transformation

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4. Symbol Legend

β – Energy [GWhrs]

μ – Specific Energy [GWh/t_{coal}]

M – Mass [t]

ŋ – Efficiency [%]

ε – Energy Content [GWh/ton]

ϑ – Specific Energy [GWh/ton-km]

ϕ – Specific Distance [$ton\text{-}km/t_{coal}$]

π – GHG Emissions [t_{CO2eq}]

α – Specific GHG Emissions [t_{CO2eq}/GWh]

ϵ - Percent Contribution [%]

A – Land Transformation [ha]

τ – Specific Land Transformation [ha/t_{coal}]

ṫ - Time [years]

d – Degradation Rate [%/year]

n – Number of Years

τ^* - Specific Land Transformation [ha/GW]

G – Solar Incidence [GWh/ha-yr]

N – Lifetime [years]

γ – CO_2 Captured by CCS During Operation [t_{CO2eq}]

μ^* - Specific Energy [GWh/ton-km]

D – Distance [km]

θ – Specific Oil Production from EOR [t_{oil}/t_{CO2}]

ρ – Leakage rate [%/year]

θ^* - Specific GHG Emissions [t_{CO2eq}/bbl]

σ – Molar Ratio of Carbon to CO_2

ω – Rate of Carbon Uptake by Switchgrass [t_C/ha-yr]

bbl – Barrel of oil

5. Introduction

It is now well established with high confidence that global climate change is underway, which is created by greenhouse gas (GHG) emissions dominated by anthropogenic energy production[52]. This has negative impacts on natural and socio-economic systems[75,101]. GHG emissions increase global temperatures[73], which in turn increase sea levels[10], extinction rates among animals[109] and also harms human health[41,83] and the stability of traditional power generation[114]. GHG emissions are dominated by carbon dioxide (CO_2)[32] with 39% of CO_2 emissions coming from traditional electrical power generation[29]. There is a clear need to mitigate climate change by reducing emissions for energy use[67,97]. This can be accomplished in part through the use of climate-neutral renewable and traditional power generation[16,39,69] and solar photovoltaics (PV) generates the most power per hectare of land among renewables[35]. Climate neutral electricity generation, where the life cycle CO_2 equivalent (CO_{2eq}) 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.

The largest source of electricity is from coal fired power plants[25]. This study focuses on pulverized coal plants that produce > 95% of the electrical output from coal. 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 here has a 1GW nameplate capacity and a capacity factor of 85%, which produces 376 TWhrs over a 50 year lifetime. When CO_2 is utilized for EOR, an additional 491 TWhrs of electricity is produced (assuming the crude oil is refined to diesel and combusted in a generator operating at 39% efficiency), totaling 866 TWhrs.

On the other hand, solar PV technology has the greatest potential to scale to provide for sustainable future among renewable sources[84], but demands larger surface areas than coal during operation[17]. PV also has embodied energy, which results in upstream emissions.

Climate neutral electricity generation can be attained by the use of carbon capture and sequestration (CCS). A combination of geological storage and biological storage is required to ensure complete mitigation. Biological storage, referred to here as bio-sequestration, is the planting of biomass to uptake carbon from the atmosphere and sequester it. A review of literature revealed that the optimal bio-sequestration is done with switchgrass.

To compare PV directly to coal plants, two fixed solar PV farms are designed to similarly produce 376 TWhrs (PVs1) and 866 TWhrs (PVs2) over a 50 year lifetime[21,58,105]. The embodied emissions from the PV farm can be roughly broken down to three main categories, modules, balance of system (BOS) and construction/decommission[47,81]. The literature review focused on using 1) studies made in the last 10 years due to the fast pace innovation of PV, 2) moderate solar insolation between 1400 and 1700, 3) multi-crystalline silicon cells, 4) large scale system >100MW and 5) performance ratio's between 0.70-0.85 to better compare to large scale coal plants.

The natural environment has a substantial capacity to store carbon near permanently, referred to here as bio-sequestration[108], but they are land area intensive so several methods are analyzed to reduce this impact from coal.

Several previous, more focused life cycle analysis (LCA) studies are aggregated here to determine the preferred approach to climate neutral electricity generation. This study compares the energy, 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 energy analysis and LCA summarized in Figure 1.

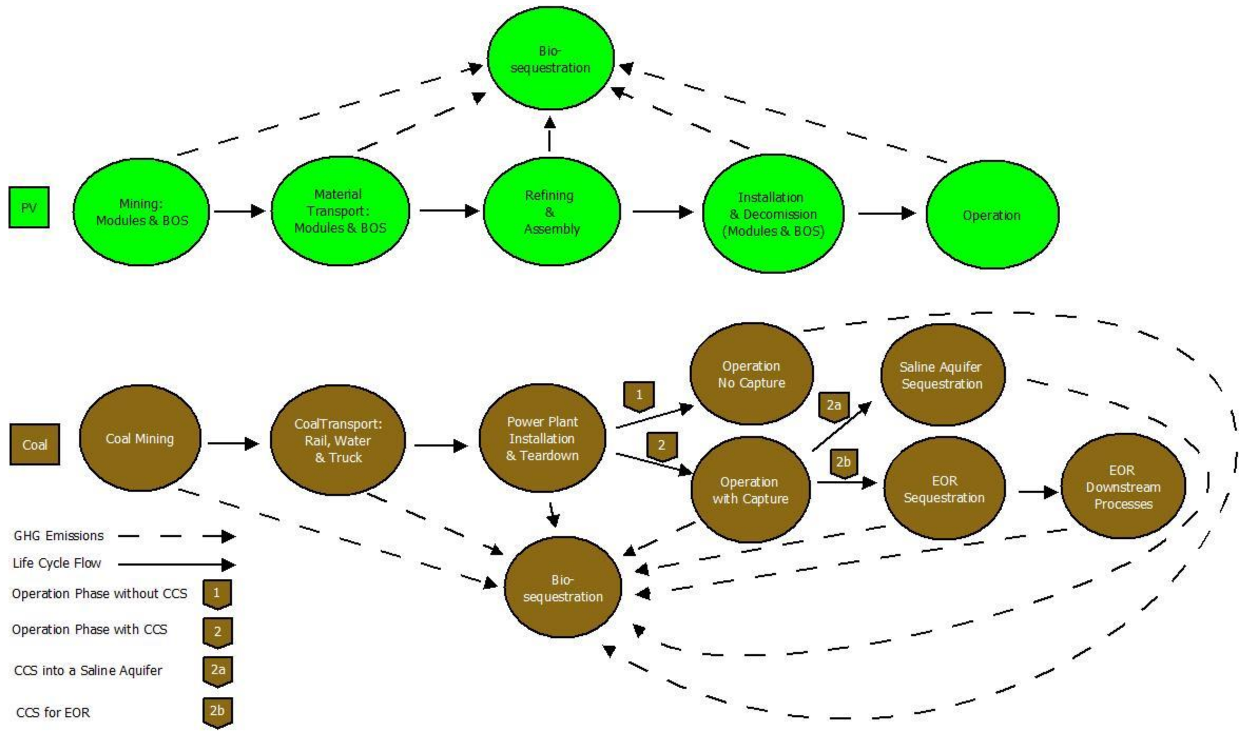

Figure 1: LCEA boundary scope for climate-neutral PV and pulverized coal electricity production. The solid arrows represent the flow of the life cycle, the dashed lines represent the CO_{2eq} of the GHG emissions uptake by bio-sequestration and the labels detail various the scenarios for the coal lifecycle.

6. Carbon Capture and Sequestration

In 2012, 411 of the 893 plants firing coal generated electricity using >95% coal and emitted $1.41x10^9$ t_{CO2eq}[8,31]. Coal's CO_{2eq} emissions demand some form of carbon capture and sequestration (CCS) in order to be climate neutral. CCS is the capture and separation of CO_2 from a fuel source, in this case it is coal. The Department of Energy (DOE) is funding 16 CCS methods, three main categories are oxyfuel combustion, pre-combustion, and post-combustion. Oxyfuel combustion is the combustion of coal in a near pure oxygen environment which produced high concentrations of CO_2 in the flue gas for easier separation. Unfortunately, it is very energy intensive and high concentrations of SO_2 create a very corrosive flue gas. Pre-combustion employs a gasification process in a low oxygen environment to produce high concentration of CO_2 for easier separation and a hydrogen rich syngas which can be combusted with near zero GHG emissions. This too is very energy intensive and complex, and there are no large scale oxyfuel plants and only a few pre-combustion plants. Post-combustion is the preferred method to date and it involves the separation of CO_2 from the flue gases, which can be done in a variety of methods which are discussed in more in the following paper[2].

The most common process to capture CO_2 from a coal plant uses monoethanolamine (MEA) post-combustion for flue gas separation. Similar ethanolamine's (amines) like diethanolamine (DEA) and methyldiethanolamine (MDEA), membranes with one and two step sweeps, pre-combustion gasification, oxyfuel combustion, solid sorbents, metal organic frameworks and others have been developed as well to separate CO_2 from coal flue gases. To date, amines are the only commercially viable method of CCS. Solvents perform best with multiple flue streams but have a high energy penalty. Amine CCS decreases the CO_2 and SO_x emissions but it also increases the ammonia and limestone consumption (from the cyclical chemical reactions in the amine process) and increases solid waste by products and NO_X (due to increase fuel consumption)[14,87,94]. Post-combustion CCS is desirable because it can be retrofit onto existing coal fired power plants. Membranes are more compact, modular, easy to install, applicable in isolated areas, have flexible operation and maintenance as well as low capital cost and lower energy penalty but cannot separate as well as amines. When CO_2 concentration is low, such as in flue gases from fossil fuel combustion, several membranes in series are required to attain a 90% capture efficiency. At CO_2 concentration > 25%, membranes cost the same as amines but the typical concentration of flue gas from pulverized coal combustion is only 12% - 14%[121]. In order to be included in this analysis, at least 80% of the carbon had to be captured. Most systems under study have a rated capture efficiency of 90%, but as evidenced from plants in operation and software models, CCS systems often have trouble reaching their rated capture efficiency[2,94,116]. These processes are energy intensive and derate the coal plant[68]. Pehnt found that when CCS is added, the energy required for operation increases 66% and it takes an additional 1.37 MJ/t_{CO2} captured[85]. In order to maintain the same output, this study assumes that more coal is combusted to offset the drop in efficiency with the addition of CCS, also called the energy penalty[94].

Subsequently, it is compressed and transported to storage locations such as deep saline aquifers, deep ocean or utilized for EOR[2]. The captured CO_2 is compressed to a supercritical state, typically above 8.6 MPa to avoid CO_2 in gaseous phase and below 15.3 MPa to avoid leaks, and transported through pipelines to the storage location[70]. Pipelines are most efficient method of transporting CO2 if lifetime is over 23 years[65]. Injection pressure for deep saline formations are between 2 – 15 MPa, depending on geologic conditions. A scale exists to rate the quality of the caprock of saline formations for storage, a 2 is weak, a 5 is moderate and a 13 is strong[50]. Deep saline aquifers at 700 – 1000 m below ground level often host high salinity formation brines and will be the focus of this study for true CO_2 storage, without utilization. Deep ocean has significant storage potential but there are serious concerns with ocean acidification and eutrophication[65]. Deep ocean storage also leaks at a rate of 0.14 – 0.30 %/yr which means it will only store 30 – 85% over a 500 year period[54]. Therefore, it was not considered in this study.

Dedicated research into CCS began in earnest after the Kyoto protocol and has received a lot of attention recently[54]. Globally, potential CO_2 storage in geological formations is between 200 – 2,000 Gt, with saline aquifers comprising the majority[38]. The National Energy Technology Laboratory demonstrates a good geographic overlap between CO_2 emission sources and depleted oil and gas reservoirs. Sequestration potential in US alone is 138 billion t_{CO2}[19]. There are currently 16 active CCS projects globally, injecting 30.15 t_{CO2}/yr with another 22 projects planned for the next 10 – 20 years[38]. Once CO_2 is sequestered in geological formations like saline aquifers and oil and gas reservoirs, it has to be monitored to quantify leakage[30], which also must be offset by bio-sequestration for climate neutrality. A popular form of CCS utilizes EOR, which pumps alternating floods of CO_2 and water into an operational oil and gas reservoir to displace more oil and gas[2]. However, all of these processes have their own downstream emissions and coupled with the remainder of the life cycle emissions, climate neutral coal-fired electricity generation requires large areas of land for bio-sequestration[108].

13 of the 16 active projects employ EOR to partially or fully sequester the CO_2. However, EOR at injection pressures between 12 – 45 MPa can increase the productivity of an oil reservoir from 25 – 55 % to 35 – 75 %. Primary drilling recovers 5 – 15 % of the available crude oil in the reservoir, also called original oil in place (OOIP) and an additional 20 – 40 % with secondary drilling, totaling 25 – 55%. Utilizing EOR increases recovery to 35 – 75 % of original oil. Approximately 280,000 barrels of crude oil per day are extracted using EOR in the U.S., which is approximately 5.1 % of total[15,26]. Additional claims state that EOR can displace an additional 5 – 15 %[19], 40 %[65] and even up to 30 – 60 % more oil[14]. The additional oil engenders GHG emissions downstream as the oil is refined and combusted. This in turn, demands further land for bio-sequestration. The land transformation from crude oil extraction operations is not included in the scope of this project. EOR is a process which increases productivity of an existing reservoir and is not thought to directly transform land by itself.

Up to 700 Mt_{CO2} can be mitigated by waste utilization alone but current utilization by industry is merely ~2%, mostly for beverages and refrigeration. Currently, 80 % of CO_2 for EOR is from natural reservoirs, not from power production plants (68 Mt_{CO2} total with 54 Mt_{CO2} from natural sources)[65].

Bio-sequestration is employed to completely offset the GHG emissions from the full life cycle of PV and coal, both with and without CCS, specifically switchgrass as it has the best rate of carbon uptake and sequestration potential[108]. Annual cropping sequesters near zero carbon[108] and is not considered in this study. The DOE Bioenergy Feedstock Development Program focused on switchgrass because of high yields, wide geographic distribution, positive effects on soil quality and stability (erosion), high nutrient use efficiency, cover for wildlife, low maintenance (energy, water, agrochemicals), good CO2 sequestration into soil, it takes 598 kgC/acre to grow switchgrass[72.] In 2000, 23% of carbon from fossil fuels are sequestered by land ~1.5 Gt of carbon (Gt_C) captured annually and in 1996 there were 120 Mha globally, which results in 45.8tC/ha on average globally for forests[9]. Temperate forests cover $1.04x10^9$ ha storing 159Gt_C. Between 1850-1998, anthropogenic carbon emissions were 270 Gt_C from fossil fuel combustion and cement production and 136 Gt_C from land use change, 176 Gt_C is in atmosphere now with the remainder of 230 Gt_C taken up equally by oceans and land. Newly planted forest will uptake CO_2 for 20 – 50 years[53]. Globally, 757 Mha of land is available for bio-sequestration with 60 Mha available in U.S., which can sequester 318 TgC/yr. Switchgrass doesn't require replanting for 15 years and can sequester carbon in soil for 40 – 60 years at a linear rate, and will continue to sequester for up to 100 years. Perennial grasses may be more suitable for carbon sequestration since short rotation woody crop like willow and poplar take time for canopy closure, making soil more prone to soil organic carbon losses[64]. Lifetime carbon capacity of soil range from 0-300 tC/ha[108].

7. Results

This study compares the energy, GHG emissions and land transformation needed for climate-neutral pulverized coal with and without utilizing various forms of CCS and climate-neutral solar PV. This section describes in detail the methods used to calculate the energy, GHG emission and land transformation. All energy input for bio-sequestration is solar in this study. Two scenario's are used to compare to climate neutral coal. PVs1 has a nameplate capacity of 5.23 GW and will output $3.76x10^5$ GWhrs over the 50 year lifetime. PVs2 has a nameplate capacity if 12.13 GW and will output $8.66x10^5$ GWhrs over the 50 year lifetime. 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 energy, GHG emissions and land transformation for all PV and coal scenarios are stated. SimaPro V8 was utilized and all energy data is from Cumulative Energy Demand V1.03 and GHG emissions data is from IPCC GWP 100a[96]. Emissions from the electrical grid are not included in the scope of the LCEA's for PV or coal.

7.1 Climate-Neutral Coal Plants

Three scenarios for carbon sequestration are analyzed: Coals1) does not use carbon capture technology at the plant, and instead uses bio-sequestration to uptake the carbon emissions and has a lifetime output of $3.76\text{x}10^5$ GWhrs, Coals2a) does use carbon capture at the plant and transports the CO_2 to a saline aquifer with remaining emissions mitigated by bio-sequestration and has a lifetime output of $3.76\text{x}10^5$ GWhrs, or Coals2b) also uses carbon capture technology at the plant and utilizes the CO_2 for EOR, with all remaining GHG emissions mitigated by bio-sequestration and has a lifetime output of $8.66\text{x}10^5$ GWhrs. The energy inputs, GHG emissions and land transformation from the upstream and operation life cycle phases are the same for Coals2a and Coals2b, and will be grouped together as Coals2 for brevity. An overview of the energy flow, GHG emissions and land transformation can be found in Tables 5 and 6.

7.1.1 Upstream

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 energy input emissions and land transformation with the tonnage of coal consumed by the plant being the main driver. In 2015, 853 mines produced $8.97\text{x}10^8$ t_{coal} with 68.50 % consumed in the U.S[20]. One particularly aggressive form of coal mining is called mountain top removal (MTR) and has above average GHG emissions and land transformation. To date, 500 MTR sites have transformed 1.4 million acres, buried 2000 miles of streams and released 2.6 Mt_{CO2eq} from soil, 27.5 Mt_{CO2eq} from mining spoil as well as 6 – 37 Mt_{CO2eq} from deforestation[34].

Upstream activities of Coals1 requires $1.08\text{ x}10^5$ GWhrs of energy input, emits $3.82\text{x}10^7$ t_{CO2eq} and transforms 17.31 kha of land for bio-sequestration. Coals2 requires $1.37\text{x}10^5$ GWhrs of energy input, GHG emissions of $4.96\text{x}10^7$ t_{CO2eq} and transforms 21.14 kha[93,96]. The carbon capture option requires more coal due to the lower efficiency plant.

The total energy required for mining coal, $\beta_{coal\ mining}$, is $6.47\text{x}10^4$ and $8.40\text{x}10^4$ GWhrs for Coals1 and Coals2, respectively, and is given by equations 1 and 2:

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

Where,

$$M_{coal} = \frac{\beta_{out}}{\eta_{coal\ plant} * \varepsilon_{coal}} \qquad [t]\ (2)$$

Where β is the energy in GWhrs, μ is the specific energy 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, ŋ is efficiency and ε is the heat content of coal in GWh/ton.

The efficiency of the plant drives the required coal energy input and ultimately the tonnage of coal required. An emphasis for the data selection is put on real conditions for state-of-the-art plants. For example, Campbell states that the top 10% of plants around the country operate at 37.6% and a review by the electric power research institute (EPRI) of subcritical plants, which are the majority in the U.S, states that they operate at 37%[7,8]. A review of the literature has found Coals1 to range from 30% – 46% with an average of 39.03% and 20.90% – 35.91% with an average of 30.03% for Coals2[2,8,24,74,111,116,120]. Table 1 has more detail.

Table 1: Overview of the energy efficiencies used in this study for coal plants with and without CCS systems.

Source	Coals1 Energy Efficiency (%)	Coals2 Energy Efficiency (%)	Notes
[94]	39.30	29.90	MEA
[120]	38.90	31.51	2 stage membrane with 2 step air sweep
		27.23	2 stage membrane
[116]	39.10	27.20	MEA
		27.90	Ammonia
[93]	36.90	29.93	Amine
[68]	39.90	27.60	MEA
		26.30	1 stage ZIF-78
		30.50	1 stage Z-5A
		26.90	1 stage SU-MAC
		26.40	2 stage ZIF-78
		20.90	2 stage Z-5A
		22.20	2 stage SU-MAC
[74] *	39.03	31.70	2 stage membrane with 2 step air sweep
		28.68	2 stage membrane
[2] *	39.03	29.81	MEA
[7]	37.00		
[111]	30.00		Average world
	40.60		Best bituminous coal plant in the world
	38.00		Average EU

[8]	37.60		Top 10% of US Fleet
[46]	37.74	34.83402	Amine
		33.24894	Amine
[65]	44	34.8	Post-combustion capture
		31.5	Pre-combustion capture
		35.4	Oxyfuel combustion
[87]	43.33	34.29	Amine
		35.09	Ammonia
		35.91	Calcium Looping
[79]	39.6	30	MEA and Selexol
[85]	46	27.8	MEA
		33.4	Oxyfuel combustion
Realistic	39.03	30.03	

*Only provided an energy penalty, so the realistic efficiency of 39.03% is assumed.

The specific mining energy for coal is 4.40×10^{-4} GWh_{in}/t_{coal}[96] and the average heat content of coal consumed by electrical power plants in the U.S. is 6.54×10^{-3} GWh/ton[84]. The amount of coal required for Coals1 is 1.25×10^{8} – 1.91×10^{8} tons, with a realistic value of 1.47×10^{8} tons[2,8,24,68,74,116,119] and is 1.63×10^{8} – 2.80×10^{8} tons with a realistic value of 1.91×10^{8} tons for Coals2[2,24,63,68,74,94,116,119,120]. This range is rather large due to the wide range of efficiencies for plants with carbon capture systems. Amines have been employed commercially on a limited scale but the remainder of the methods are in various stages of conceptualization.

The total energy required for transporting coal, $\beta_{coal\ transport}$, is 3.07×10^{4} and 3.98×10^{4} GWhrs for Coals1 and Coals2, respectively, and is given by equations 3 and 4:

$$\beta_{coal\ transport} = (\mu_{coal\ transport,rail} + \mu_{coal\ transport,marine} + \mu_{coal\ transport,truck}) * M_{coal} \quad \text{[GWhrs]} \quad (3)$$

Where,

$$\mu = \vartheta * \varphi \qquad [GWh/t_{coal}] \ (4)$$

Where ϑ is the specific energy 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-km[96]. 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-km[96].

The energy required for construction, $\beta_{coal\ construction}$, is 1.29×10^{4} GWhrs for Coals1 and Coals2 and is calculated by equation 5:

$$\beta_{coal\ construction} = \Sigma(M_{coal\ materials} * \mu_{coal\ materials}) \qquad \text{[GWh] (5)}$$

Where $M_{coal\ materials}$ is the tonnage of individual materials[107] and $\mu_{coal\ materials}$ is the specific energy of the materials in GWh/t[96]. Total construction energy is 11.94% of the total energy required by upstream activities, detailed in Table 2. The energetic input required for the procurement of the additional equipment for compressing the CO_2 is assumed to be negligible.

Table 2: Construction energy for a climate neutral coal plant outputting 376 TWhrs of electricity over the 50 year lifetime (Coals1).

	Material	Mass (tons)[58]	Specific Energy Input (GJ/ton)[33]	Energy Input (GWh)
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
	El. In	0	1.27×10^4	1.27×10^4
	Oil	7.09×10^2	4.08×10^1	8.09
	Coal in	1.43×10^4	6.83×10^{-6}	9.80×10^1
	Total for 1GW plant	2.56×10^5		1.29×10^4

Total upstream greenhouse gas emissions for a 1GW coal plant, $\pi_{coal\ upstream}$, are 3.82×10^7 and 4.96×10^7 t_{CO2eq} for Coals1 and Coals2, respectively and are given by equation 6:

$$\pi_{coal\ upstream} = \left(\left((\alpha_{coal\ mining} * \epsilon_{coal\ mining}) + (\alpha_{coal\ transport} * \epsilon_{coal\ transport})\right) * M_{coal}\right) + (\alpha_{coal\ construction} * \beta_{yealy\ output}) \qquad [t_{CO2eq}]\ (6)$$

Where α is the specific emissions in t_{CO2eq}/t_{coal}, ϵ is the percent contribution and $\beta_{yealy\ output}$ is the energy 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}[96]. Total upstream emissions have also been calculated to be 55 t_{CO2eq}/GWh_{out}, and when multiplied by the electricity output and divided by the tonnage of coal, results in 0.12 t_{CO2eq}/t_{coal}[56]. The average of these two values provides a realistic upstream emission factor of 0.27 t_{CO2eq}/t_{coal}. The yearly output is simply the lifetime output divided by 50 years, which is 7.51 TWhr/yr when the lifetime output is 376 TWhrs and 17.32 TWh/yr when the lifetime output is 866 TWhrs.

Mining emissions for Coals1 range between 1.14×10^7 – 4.74×10^7 t_{CO2eq} with a realistic value of 2.10×10^7 t_{CO2eq} and 8.74×10^6 – 3.44×10^7 t_{CO2eq} with a realistic value of 2.73×10^7 t_{CO2eq} for Coals2[56,96]. Transport emissions for Coals1 range between 9.30×10^6 – 3.88×10^7 t_{CO2eq} with a realistic value of 1.72×10^7 t_{CO2eq} and 7.15×10^6 – 2.81×10^7 t_{CO2eq} with a realistic value of 2.23×10^7 t_{CO2eq} for Coals2[56,96]. The ranges of these values are rather large. Originally, only values from the software SimaPro were utilized, but data from literature is included and aggregated here to give the reader an idea of the subjectivity of this facet of the life cycle.

Land transformation for upstream activities, $A_{coal\ upstream}$, are 17.31 kha and 21.14 kha for Coals1 and Coals2, respectively and calculated by equation 7:

$$A_{coal\ upstream} = \left(\tau_{coal\ mining} + \tau_{coal\ transport}\right) * \beta_{out} \qquad \text{[kha] (7)}$$

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 used[6] with 8.97×10^8 tons of coal mined each year[81] giving an average of 1.52×10^{-4} ha/t_{coal}. Surface mining transforms 90-1820 m^2/kt with a realistic value of 300 m^2/kt and underground mining transforms 4.5-1110 m^2/kt with a realistic of 30 $m^2/kton$[35]. Determining accurate data for land transformation by coal is difficult based on the plethora of overlapping government bodies and inconsistent collection of data from year to year. The annual coal reports from the Office of Surface Mining, Reclamation and Enforcement (OSMRE) are used in conjunction with several sources to provide an updated range[6]. More information on this can be found in Appendix A. Given that on average 70% of the coal mined in the U.S. is from surface mining and 30% from underground mining[35], 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 m^2/GWh in the east to 80 m^2/GWh in the west[35]. Given that 88% of coal shipped to electrical power plants is by rail and another 11% by water[96] it is assumed that 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 east[23] so a realistic value was assumed to be 5.75×10^{-3} ha/GWh. Land use per t_{coal} for Coals1 and Coals2 is 1.03×10^{-5} ha/t_{coal} and 1.42×10^{-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.

7.1.2 Operation

During the operation of the coal plant, the effects of adding carbon capture technologies is studied. Additional coal input is used to offset the energy penalty due to carbon capture to ensure a 1GW nameplate capacity. A typical state-of-the-art coal plant drops from an efficiency of 39.03% to 30.03% with the addition of carbon capture technology[2,8,68,93,116]. See Table 1 for more detailed information. CCS drops LCA efficiency from 36.3 to 27.7%[79]. If the upstream energy input is subtracted from the energy output, then the LCA efficiency based on the realistic data aggregated for this study drops from 39.03% to 27.78% for Coals1, 19.10% for Coals2a and 27.64% for Coals2b. This results in $9.62x10^5$ and $1.25x10^6$ GWhrs of coal energy required for Coals1 and Coals2, respectively. As well as $1.39x10^6$ GWhrs of energy from oil for Coals2b. GHG emissions total to $3.38x10^8$ and $6.07x10^7$ t_{CO2eq} for Coals1 and Coals2, respectively[56,96]. For Coals1, the total land required is 361 kha, with bio-sequestration transforming 344 kha[,81,112]. For Coals2a and Coals2b, the total land transformation is 132 kha and 307 kha. The physical area required for the plant is considered equal for all coal scenarios at 202 ha[35]. The land transformation for Coals2b is conservative as it does not include data on the life cycle of crude oil extraction and eventual combustion.

The energy into the coal plant during operation is comprised entirely from the latent energy in the coal. The energy inputs required, $\beta_{coal\ operation}$, are $9.62x10^5$ and $1.25x10^6$ GWhrs for Coals1 and Coals2, respectively and are calculated by equation 8:

$$\beta_{coal\ operation} = \frac{\beta_{out}}{\eta_{plant}} \qquad \text{[GWhrs] (8)}$$

For Coals1, between $8.16x10^5$ – $1.25x10^6$ GWh with a realistic value of $9.62x10^5$ GWhrs are of coal energy are required.[2,8,68,94,111,116,120]. Coals2 ranges between $1.07x10^6$ – $1.83x10^6$ GWhrs with a realistic value of $1.25x10^6$ GWh[2,63,68,74,94,116,120]. Thus, carbon capture technology has an energy penalty of 29.94%, which creates additional GHG emissions released to the atmosphere to offset.

The most common and technologically mature method of carbon capture at the plant is post-combustion capture using MEA. The efficiency drop due to CCS comes from the high energy intensity of the carbon capture process and the compression of the CO_2. Large-scale MEA processes can consume 92 – 119 MW_{el} and an additional 0.72 – 1.74 $MW_{th}/MW_{eloutput}$. This results in and average of 0.11 GW_{el} and 0.99 GW_{th} for a ~1GW power plant[93]. These values are conservative because the carbon capture efficiency in the study was 60 – 65 %. Table 3 shows how variable the energy consumptions for different CCS systems may be.

Table 3: The variation in energy penalties from different forms of carbon capture at coal plants[63].

Type of carbon capture	Energy Required ($kWh/t_{CO2\ captured}$)
Amine operation	335
Membrane operation	72.5
Cryogenic operation	625

Pressure Swing Adsorption operation	170

The GHG emissions to the atmosphere during operation, $\pi_{coal\ operation}$, are 3.41x10^8 and 6.87x10^7 t_{CO2eq} for Coals1 and Coals2, respectively and are calculated by equation 9:

$$\pi_{coal\ operation} = \alpha_{coal\ operation} * \beta_{out} \qquad [t_{CO2eq}]\ (9)$$

Where the specific GHG emissions from coal plants without carbon capture range from 807 – 1100 t_{CO2eq}/GWh, with a realistic value of 907 t_{CO2eq}/GWh[14,79,85,87,98,112,119]. Emissions from plants with capture range from 124 – 203 t_{CO2eq}/GWh, with a realistic value of 182 t_{CO2eq}/GWh[2,98,14,119,85,79]. If the effect of commissioning and decommissioning new CO_2 pipeline infrastructure is included, then GHG emissions of plants with CCS can reach 402.21 t_{CO2eq}/GWh with calcium looping, 495.93 t_{CO2eq}/GWh with amines and 500.83 t_{CO2eq}/GWh with ammonia[101], but this study assumes the use of existing infrastructure. The carbon capture efficiency in this study ranges from 81% - 91% capture of total emissions[2,63,68,74,93,94,116,120].

Land transformation caused by the plant itself, $A_{coal\ operation}$, is 202 ha for Coals1 and Coals2 and calculated by equation 10:

$$A_{coal\ operation} = \tau_{coal\ operation} * \beta_{out} \qquad [kha]\ (10)$$

Where the specific land transformation ranges from 6.0x10^{-4} – 3.3x10^{-3} ha/GWh_{out}, with an average of 9.0x10^{-4} ha/GWh_{out}[35,71].

7.1.3 Downstream

7.1.3.1 Coals1

In power plants without CCS, the energy from solar irradiation for bio-sequestration is 2.58x10^7 GWhrs. The total emissions will be bio-sequestered by switchgrass, which will uptake enough carbon to offset 3.79x10^8 t_{CO2eq} and transform 344 kha of land.

The energy input from solar irradiation for bio-sequestration of GHG emission from Coals1, $\beta_{coal\ bio}$, is 2.58x10^8 GWhrs and calculated by equation 11:

$$\beta_{coal\ bio} = G * N * A_{coal\ bio} \qquad [GWhrs]\ (11)$$

Where G is the average U.S. solar incidence of 15,000 GWh/ha*yr[118], N is the number of years over its lifetime and $A_{coal\ bio}$ is the land transformation required by the switchgrass for upstream and operation activities without CCS in hectares.

The total GHG emissions released to the atmosphere from Coals1 to be offset by bio-sequestration, $\pi_{coal\ bio}$, equals 3.79x10^8 t_{CO2eq} and calculated by equation 12:

$$\pi_{coal\ bio} = \pi_{coal\ upstream} + \pi_{coal\ operation} \qquad [t_{CO2eq}]\ (12)$$

The land transformation required for bio-sequestration for Coals1, $A_{coal\ bio}$, is 344 kha and calculated by equation 13:

$$A_{coal\ bio} = \frac{\pi_{coal\ bio} * \sigma}{\omega * N} \qquad [kha]\ (13)$$

Where σ is the molar ratio of carbon to CO_2,which is $(\frac{12}{44})$ and ω is the rate of carbon uptake by switchgrass, which is 6 t_C/ha-yr[64]. The total land transformation for Coals1 is 362 kha.

<u>7.1.3.2 Coals2a</u>

In the U.S., EOR is focused around Texas because it has several natural CO_2 reservoirs. The largest EOR operation has 414 CO_2 injection wells and 354 production sites, so the incremental energy from drilling more wells is difficult to ascertain[38]. The sum of GHG emissions produced from both upstream and operation phases are 4.43x10^8 t_{CO2}, with 3.74x10^8 t_{CO2} captured and transported to the saline aquifer. This results in the bio-sequestration of 6.83x10^7 t_{CO2} that were released to the atmosphere[14,98.112]. The slight discrepancy in uptake by bio-sequestration is from the emissions due to leakage. The total land transformation is 134 kha, with bio-sequestration requiring 112 kha alone[54,81,108,112,114].

The energy input for bio-sequestration of GHG emissions from Coals2a, $\beta_{coal\ CCS}$, is 8.43x10^7 GWhrs and calculated by equation 14-16:

$$\beta_{coal\ CCS} = \beta_{coal\ CCS\ bio} + \beta_{CO2\ cond} \qquad [GWhrs]\ (14)$$

$$\beta_{coal\ CCS\ bio} = G * N * A_{coal\ CCS\ bio} \qquad [GWhrs]\ (15)$$

$$\beta_{CO2\ cond} = \mu_{CO2\ cond} * \gamma \qquad [GWhrs]\ (16)$$

Where $A_{coal\ CCS\ bio}$ is the land transformation required by the switchgrass for upstream, operation and downstream activities with CCS into a saline aquifer in hectares, $\mu_{CO2\ cond}$ is the specific energy required to condition the CO_2 (compress and transport) after its been separated and measured in GWh/t_{CO2} and γ

is the difference between the CO_2 released to the atmosphere during operation by Coals1 and Coals2 in t_{CO2}, which can also be thought of as the total CO_2 captured in t_{CO2}. The specific energy required to compress CO_2 to 8.6 – 15.3 MPa is between 112 – 119 kWh/t_{CO2}, realistically being 116 kWh/t_{CO2}[70,93,118]. The pipelines have been found to lose between 4 – 50 kPa per 100 km[118], thus requiring 6.5 kWh/t_{CO2} to boost the pressure for longer transport[56] but the assumption in this study is that no pressure boosters are required. The average distance for CO_2 to travel for sequestration purposes is 190.5 km[38] and the Weyburn case demonstrates that CO_2 can be transported 330 km without additional boosting energy[118].

The total CO_{2eq} captured is the difference between GHG emissions from a Coals1 and Coals2, which are 3.41x10^8 t_{CO2eq} and 6.83x10^7 t_{CO2eq}, respectively. Making the difference between them be 2.72x10^8 t_{CO2}.

The total GHG emissions released to the atmosphere from Coals2a, $\pi_{coal\ CCS}$, is 1.23x10^8 t_{CO2eq} where the total leaked are 3.53x10^6 t_{CO2eq} and calculated by equation 17 and 18:

$$\pi_{coal\ CCS} = \pi_{coal\ upstream} + \left(\pi_{coal\ operation} * (1-\gamma)\right) + \pi_{leak} \qquad [t_{CO2eq}]\ (17)$$

Where,

$$\pi_{leak} = \left(\rho_{reservoir} * N * \gamma\right) + \left(\alpha_{CO2\ transport} * D_{CO2}\right) \qquad [t_{CO2eq}]\ (18)$$

Where $\rho_{reservoir}$ is the leakage rate from the oil and gas reservoir in %/yr, $\alpha_{CO2\ transport}$ is the specific emissions from the pipeline transport of CO_2 in t_{CO2}/km, D_{CO2} is the distance CO_2 travels in the pipe from the plant to the reservoir in km. Currently, 28.3 Mt_{CO2}/yr are used for EOR[38]. Reports from commercial operations like Weyburn and Sleipner report zero leakage[38,99]. But this imprecise reporting may be due to the guidelines released by the EPA entitled "Federal Requirement under the geologic injection control program for CO2 geologic sequestration wells final rule" which mandates that CO_2 storage in geologic formations be monitored and be completely free of leakage. There are 4 main leakage pathways, drilled wells, improper plugs, caprock faults and underground drinking water[28]. Proposed leakage rates should target 0.1%/yr for smaller projects and 0.01%/yr[43] while the IPCC gives more stringent leakage rates of 0.01 – 0.001 %/yr[54]. Leakage rates at less than 0.001%/yr have been reported[19]. Any leakage rate of 0.1%/yr or higher would render the storage ineffective[27]. The realistic leakage rate used in this study is 0.0275 %/yr.

The land transformation of Coals2a, $A_{coal\ CCS}$, is 112 kha and calculated by equation 19:

$$A_{coal\ CCS} = \frac{(\pi_{coal\ bio} + \pi_{leak}) * \sigma}{\omega * N} \qquad [kha]\ (19)$$

The land transformation ranges from 61 – 309 kha. The wide distribution is due to compounding effect of the ranges from GHG emissions in earlier phases of the life cycle.

7.1.3.3 Coal2b

In power plants with CCS for EOR, the coal energy input is the same as Coals2a but the subsequent downstream activities require 1.92x10^6 GWhrs of energy input. Over the complete life cycle, the total energy input is 2.19x10^8 GWhrs. The GHG emissions to the atmosphere from sequestering CO_2 with EOR and further processes for oil combustion is 1.98x10^8 t_{CO2eq}. The total GHG emissions of the life cycle, 3.16x10^8 t_{CO2eq}, will need to be bio-sequestered[14,38,56,96,98,112], which necessitates 309 kha of total land transformation with 287 kha for bio-sequestration[54,56,81,102,108,112,114].

The downstream processes for EOR also produce additional energy output. In order to give a direct comparison to PV, the energy output from EOR-based refined product is combusted in a generator with an efficiency of 39%[22] to generate electricity. The total lifetime energy output for the EOR scenario becomes 866 TWhrs net electricity. In order to accommodate this, an additional PV scenario (PVs2) with an equivalent output is employed and compared to Coals2b.

The energy input for bio-sequestration of GHG emission from Coals2b, $\beta_{coal\ EOR}$, is 2.16x10^8 GWhrs and calculated with equation 20 - 24:

$$\beta_{coal\ EOR} = \beta_{coal\ bio} + \beta_{coal\ CCS\ bio} + \beta_{oil\ extraction} + \beta_{oil\ transport} + \beta_{oil\ refine} \quad \text{[GWhrs] (20)}$$

Where,

$$\beta_{oil\ extraction} = \mu_{oil\ extract} * M_{oil} \quad \text{[GWhrs] (21)}$$

$$\beta_{oil\ transport} = \mu^{*}_{oil\ transport} * M_{oil} * D_{oil} \quad \text{[GWhrs] (22)}$$

$$\beta_{oil\ refine} = M_{oil} * \left(1 - \eta_{refinery}\right) * \varepsilon_{oil} \quad \text{[GWhrs] (23)}$$

Where,

$$M_{oil} = \gamma * \theta_{oil} \quad \text{[t] (24)}$$

And where $\mu_{oil\ extract}$ is the specific energy 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 energy 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 4.40x10^{-5} – 1.38x10^{-4} GWh/t_{oil}, with a realistic value of 7.40x10^{-5} GWh/t_{oil} to extract crude oil[62,63]. The energy required for recycling and re-injecting the CO_2 continuously ranges between 3.21 – 9.00 kWh/$t_{CO2\ injected}$, with a realistic value of 6.10 kWh/$t_{CO2\ injected}$[56,62]. The energy required for recycling the CO_2 is captured under the extraction energy.

An additional exergetic input of 8.15x10^8 GWh/t_{oil} is needed to transport it to a refinery and the average distance crude oil travels to a refinery is 1200km[56].

A typical refinery operates at 90.1% efficiency[117] and approximately 93%[32] of this turns into combustible products[56]. The crude oil was assumed to have a heat content of 1.17x10^{-2} GWh/ton[62] and all the refined product to have a heat content of 1.14x10^{-2} GWh/ton[96]. The energy required to transport the refined product is considered negligible[56].

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 $t_{oil}/t_{CO2\ injected}$,[26,45,62,102]. More detailed information can be found in Table 4.

The amount of oil produced by Coals2b ranges between 6.25x10^7 – 4.08x10^8 t_{oil} with a realistic value of 1.60x10^8 t_{oil}.

Table 4: Overview of the efficiency of EOR in crude oil production as a function of CO_2 injection quantities.

Source	**EOR Productivity (t_{oil}/t_{CO2})**
[26]	0.25
[45]	0.61
[62]	0.18
	0.40
[102]	0.23
	0.89

The energy content of crude oil is 41.9 GJ/ton[62]. Energy input from the heat content of the crude oil, β_{oil}, ranges between 5.43x10^5 – 3.50x10^6 GWhrs with a realistic value of 1.39x10^6 GWhrs. This large range is due to the variation in oil production from EOR, as detailed above.

The total GHG emissions released to the atmosphere from Coals2b, $\pi_{coal\ EOR}$, are 3.15x10^8 t_{CO2eq} and calculated by equation 25 and 26:

$$\pi_{coal\ EOR} = \pi_{coal\ CCS} + \pi_{EOR} \qquad [t_{CO2eq}]\ (25)$$

Where,

$$\pi_{EOR} = \left[(\rho_{extraction}) + \left[\left(\theta^*_{transport} + \theta^*_{refine} + \theta^*_{combust}\right) * \varepsilon_{oil}\right]\right] * \gamma \qquad [t_{CO2eq}]\ (26)$$

Where $\rho_{extraction}$ is the CO_2 released to the atmosphere during the recycling and re-injection and θ^* is the specific emissions in t_{CO2}/bbl, where 7.33 bbl equate to one metric ton of crude oil.

The downstream processes of EOR emit significant amounts of greenhouse gas. Separating and recycling the CO_2 for re-injection is important to curtail emissions during EOR. It allows the user to purchase less CO_2 and is the norm. The process of EOR is the use of alternating floods of water and CO_2 gas are injected into oil deposits to increase oil production. For EOR optimized for carbon sequestration, it can take months for the CO_2 to start being extracted with the crude oil and will continue to be extracted for years after flooding has stopped[102]. During crude oil extraction, 6 – 13.7 % of the total injected CO_{2eq} is lost to the atmosphere when assuming that CO_2 is injected for 10 years and then recycled for another 10 years[63,102,104]. 11% of these losses come from recycling, 38 % from venting CO_2 and 42% from venting CH_4[102].

Many EOR projects do not employ the most efficient storage process. Stewart [102] shows how increased oil productivity can be achieved by continuously injecting new CO_2 or how increased storage of CO_2 is attained by injecting CO_2 for part of the extraction time and using a recycling process to re-inject the CO_2 again for the remainder. Sequestration in EOR varies by process and by reservoir, ranging from 64 Mt_{CO2} injected and 35 Mt_{CO2} actually stored[45], 40 – 50 % of CO_2 is stored during EOR[1], injected 43 Mt_{CO2} and stored 18 Mt_{CO2}[27]. In this study, $2.72x10^8$ t_{CO2} are captured at the plant in Coals2. When utilized for EOR it will produce and additional $1.60x10^8$ t_{oil} which emit $1.98x10^8$ t_{CO2eq} that must be offset with bio-sequestration. In effect, over the full life cycle, EOR will sequester 27.21% of the CO_2 injected.

Transport of crude oil to the refinery emits $4x10^{-3}$ t_{CO2eq}/bbl, refining the crude emits $3x10^{-2}$ t_{CO2eq}/bbl and combusting the refined product emits 0.43 t_{CO2eq}/bbl[102]. Transportation of the refined product is considered negligible[56].

The leakage rates are not delineated between saline aquifers and oil and gas reservoirs in literature, but are grouped together as geological storage. The target for leakage from geological storage, like that used in saline aquifers and EOR, should be between $1x10^{-2}$ – $1x10^{-1}$ %/yr or $1x10^{-3}$ – $1x10^{-2}$ %/yr[43,54], so a realistic value of $2.75x10^{-2}$ %/yr is used. There are over 6500km of CO2 piped for EOR globally and 4500 km of CO_2 pipelines[18,77] in the U.S which leak $4.64x10^7$ t_{CO2eq} each year[32], resulting in emissions of $1.03x10^4$ t_{CO2eq}/km. The average distance between a CO_2 source and sink is 190.5 km[38]. Most of the infrastructure for CO_2 pipelines are in Texas, connecting natural CO_2 reservoirs to active oil and gas fields for EOR, ~80% of all CO_2 transported is from natural reservoirs[18].

The land transformation of Coals2b, $A_{coal\ EOR}$, is 287 kha, respectively and calculated using equation 27:

$$A_{coal\ EOR} = \frac{(\pi_{coal\ bio}+\pi_{leak}+\pi_{EOR})*\sigma}{\omega*N} \quad \text{[kha] (27)}$$

Unless otherwise noted, this study assumed CO_2 transport was performed using existing pipeline infrastructure. In this regard, land transformation for EOR is slightly conservative.

A detailed breakdown of the energy flow, emissions and land transformation of the life cycles of Coals1 and Coals2a can be found in Table 5 while Coals2b can be found in Table 6. They are split by energy output, for a better comparison to the respective PV scenario.

Table 5. Overview of energy flow, emissions and land transformation by life cycle phase in a climate neutral coal plant outputting 376 TWh (Coals1 and Coals2a) of electricity over its lifetime.

Life Cycle Phase	Source/ Sink	$Energy_{in}$ (GWh)	$Energy_{out}$ (GWh)	Emissions (t_{CO2eq})*	Land Transformation (ha)
Coals1 Upstream	Mining	6.47×10^4 [2,68,116,8,24,94,119,120,111,74]		2.10×10^7 [96,56]	1.28×10^4 [81,35,6]
	Transport	3.07×10^4 [96]		1.72×10^7 [96,56]	4.32×10^3 [96,35,23]
	Construction	1.29×10^4 [96,107]		1.66×10^5 [96,107]	N/A
	Total	1.08×10^5 [2,68,116,8,24,94,119,120111,74,96,107]		3.82×10^7 [96,56,107]	1.73×10^4 [81,35,6,96,23]
Coals2 Upstream	Mining	8.40×10^4 [2,68,116,8,24,94,119,120,111,74]		2.73×10^7 [96,56]	1.66×10^4 [81,35,6]
	Transport	3.98×10^4 [96]		2.23×10^7 [96,56]	4.32×10^3 [96,35,23]
	Construction	1.29×10^4 [96,107]		1.66×10^7 [96,107]	N/A
	Total	1.37×10^5 [2,68,116,8,24,94,119,120,111,74, 96,107]		4.96×10^7 [96,56,107]	2.11×10^4 [81,35,6,96,23]
Coals1 Operation	1GW Plant	9.62×10^5 [2,68,116,8,94,120,111]	3.76×10^5	3.41×10^8 [112,98,14,109]	2.02×10^2 [35]
Coals2 Operation	1GW Plant	1.25×10^6 [2,68,93,116,94,120,74,63]	3.76×10^5	6.83×10^7 [2,112,98,14,119]	2.02×10^2 [35]
Coals1 Downstream	Bio-sequestration	2.58×10^8 [112,96,56,98,14,119,107,118,64,88]		-3.79×10^8 [112,96,56,98,14,119,107]	3.44×10^5 [112,96,56,98,14,119,107,64,88]
Coals2a Downstream	Bio-sequestration	8.43×10^7 [32,2,54,38,112,96,116,56,98,14,119,107,118,64,88,18]		-1.23×10^8 [32,2,54,38,112,96,116,56,98,14, 119,107,118,88,18]	1.12×10^5 [32,2,54,38,112,96,116,56,98,14,119,107,118,88,18,64]
	CO_2 Conditioning	2.64×10^4 [93,118]		1.97×10^6 [32,38]	N/A
	CO_2 Injection	1.57×10^3 [56,62]		N/A	N/A
	Geologic Leakage	N/A		3.53×10^6 [54,43]	N/A

*carbon sequestration is given as negative and carbon equivalent emissions as a positive numbers.

Table 6: Overview of energy flow, emissions and land transformation by life cycle phase in a climate neutral coal plant utilizing EOR (Coals2b) for an additional output of 491 TWhrs of electricity over the lifetime, totaling 866 TWhrs.

Life Cycle Phase	Source/ Sink	$Energy_{in}$ (GWh)	$Energy_{out}$ (GWh)	Emissions (t_{CO2eq})*	Land Transformation (ha)
Coals2 Upstream	Mining	$9.21x10^4$ [2,68,116,8,24,94,119,120,111,74]		$2.94x10^7$ [96,56]	$1.82x10^4$ [34,42,59]
	Transport	$4.37x10^4$ [96]		$2.40x10^7$ [96,56]	$4.32x10^3$ [33,42,60]
	Construction	$1.29x10^4$ [96,107]		$1.66x10^7$ [96,107]	N/A
	Total	$1.49x10^5$ [2,68,116,8,24,94,119,120,111,74,96,107]		$5.34x10^7$ [96,56,107]	$2.27x10^4$ [33,34,42,59,60]
Coals2 Operation	1GW Plant	$1.37x10^6$ [2,68,93,116,94,120,74,63]	$3.76 x10^5$	$6.07x10^7$ [2,112,98,14,119]	$2.02x10^2$ [42]
Coals2b Downstream	Bio-sequestration	$2.16x10^8$ [32,2,54,38,26,112,96,116,56,98,14,102,119,63,107,118,62,117,45,13,64,88,18]		$-3.16x10^8$ [32,2,54,38,112,96,116,56,98,14,102,119,107,118,62,88,18]	$2.87x10^5$ [32,2,54,38,112,96,116,56,98,14,119,107,118,62,88,18,64]
	CO2 Conditioning	$2.64x10^4$ [93,118]		$1.97x10^6$ [32,38]	N/A
	Crude Extraction	$1.18x10^4$ [2,26,116,98,14,102,119,63,62,45,13]		$3.51x10^7$ [2,116,98,14,102,119]	N/A
	CO2 Injection/ Recycling	$1.57x10^3$ [2,26,116,98,14,102,119,63,62,45,13]		$3.87x10^6$ [2,116,98,14,102,119,62]	N/A
	Crude Transport	$2.51x10^4$ [2,26,116,98,14,102,119,62,45,13]		$1.35x10^6$ [2,116,98,14,102,119,62]	N/A
	Crude Refining	$1.85x10^6$ [2,26,116,98,14,102,119,63,62,45,13]		$1.02x10^7$ [2,116,98,14,102,119,62]	N/A
	Petroleum Combustion	N/A	$4.91x10^5$	$1.46x10^8$ [2,116,98,14,102,119,62]	N/A
	Goelogic Leakage	N/A		$3.53x10^6$ [54,43]	N/A

*carbon sequestration is given as negative and carbon equivalent emissions as a positive numbers.

Additional information in EOR productivity and leakage rates can be found in Appendix B.

7.2 Climate-Neutral Solar Photovoltaic Farms

7.2.1 Upstream

The upstream energy input, emissions and land transformation can be separated into three categories, modules, BOS and construction of the PV farm. In short, the production process of silicone (Si) PV is to 1) mine quartz, 2) refine to elemental Si in arc furnace 3) further refine to PolySi (which has toxic waste that needs proper disposal), 4) mold and slice into wafers 5) add impurities to create PN junction 6) recycle $SiCl_4$ to recapture Si[77]. The process of refining to PolySi consumes 45% of the primary upstream energy and the equipment required to recycle $SiCl_4$ costs tens of millions of dollars rendering its application infrequent[36]. In keeping with the focus on comparing average PV to state-of-the-art coal fired plants, multi-crystalline silicone is analyzed. It has slightly better power per t_{CO2} than monocrystalline where the comparatively better efficiency of monocrystalline is offset by the higher upstream energy requirements[86].

For PVs1 and PVs2, the energy input is 2.00x10^4 and 4.60x10^4 GWhrs. The GHG emissions are 9.99x10^6 and 1.99x10^7 t_{CO2eq} and the land transformations are 0.58 kha and 1.11 kha for upstream activities[112,96,35,95,37,71].

The energy required for upstream activities, $\beta_{PV\ upstream}$, is 2.00x10^4 GWhrs for PVs1 and 4.60x10^4 GWhrs for PVs2 and is calculated by equation 28:

$$\beta_{PV\ upstream} = \left(\dot{t}_{EPB} * \beta_{yearly\ output}\right) + \beta_{PV\ construction} \qquad \text{[GWhrs]} \quad (28)$$

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[5,37,48,86,95]. Individually, the energy contribution from the modules and BOS are 63% and 37% of the total, respectively[4]. Many LCA's in literature chose to write their upstream energy content as EPBT, but several LCA's aggregated by Bhandari [5] show an average energy input of 3914 +/- 2212 MJ/m^2. PVs1 and PVs2 were modelled in System Advisor Model (SAM), which results in an energy input of 4.79x10^4 GWhrs for PVs1 and 1.10x10^5 GWhrs for PVs2. The data gathered from SAM was among the higher end of data from literature. The assumptions used in SAM were of a solar insolation of 1700 kWh/m^2/day, a module efficiency of 12.3% (with 0.49%/yr degradation) and a PR of 0.75. Giving an EPBT of 3.5 +/- 1.5 years.

The construction energy was calculated by multiplying the tonnage of material by the upstream energy for each material[96,107], as seen in table 7.

Table 7: GHG emission for the construction of a 5.23 GW PV farm outputting 376 TWhrs over the 50 year lifetime (PVs1).

Material	Mass (ton)[107]	Specific Emissions (t_{CO2eq}/ton)[96]	Emissions (t_{CO2eq}/ton)[96,107]
Steel	1.04x10^3	2.25x10^2	2.33x10^5

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	
Copper	1.08×10^{2}	N/A	
El. Energy in	1.70	8.12×10^{2}	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 Construction emissions	2.19×10^{3}		2.52×10^{5}

The upstream GHG emissions, $\pi_{PV\ upstream}$, are 9.99×10^{6} t_{CO2eq} and 1.99×10^{7} t_{CO2eq} for PVs1 and PVs2, respectively and is calculated with equation 29:

$$\pi_{PV\ upstream} = \left(\alpha_{PV\ upstream} * \frac{\beta_{out}}{\delta}\right) + \pi_{PV\ construction} \qquad [t_{CO2eq}]\ (29)$$

Where α_{PV} is the specific GHG emissions in t_{CO2eq}/GWh_{out} and δ is the ratio of the 50 year lifetime assumed in this paper and the lifetime assumed in the literature referenced. The specific GHG emissions range between 7 – 187 t_{CO2eq}/GWh_{out}, with a realistic value of 47 t_{CO2eq}/GWh_{out}[36,37,48,49,86,95103,112] . The range here illustrates the importance of aggregating many LCA's to find a realistic value. The upstream emissions are highly dependent on the technology/processes used to produce the modules as well as the distance between production and implementation. In all, 28 LCA's were reviewed to find a realistic number. The individual contributions of modules and BOS to total emissions are 38.9% and 61.1%, respectively[4]. The emissions from construction are detailed in Table 3. LCAs screened assumed a lifetime of 20-30 years. Assuming the inverters needs maintenance and replacement every 10-15 years, we can conservatively assume four replacements, which results in 0.008 kWh/W[48] and 0.042 GWhrs and 0.097 GWhrs for PVs1 and PVs2 over the lifetime of the systems. This paper asserts that PV systems can last 50 years with a negligible amount of GHG emissions after the first 25 years[21,58,105,].

Land transformation from upstream activities, $A_{PV\ upstream}$, are 0.58 kha and 1.11 kha for PVs1 and PVs2, respectively and is calculated with equation 30:

$$A_{PV\ upstream} = (\tau_{PV\ modules} + \tau_{PV\ BOS}) * \frac{\beta_{out}}{\delta} \qquad [kha]\ (30)$$

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, respectively[35]. The upstream land transformation for materials and processes specific to construction of the PV farm have not been reported on heavily. The size of the farm is the key driver to this and utility scale farms have only become viable recently. Therefore, they were not included in this study so total values can be considered conservative.

7.2.2 Operation

In the operation phase, the solar irradiation accounts for the entirety of the energy input, $\beta_{PV\ operation}$, totaling 4.30x10^6 and 9.91x10^6 GWhrs for PVs1 and PVs2, respectively and is calculated by equation 31 and 32:

$$\beta_{PV\ operation} = \Sigma\left(\frac{\beta_{yearly\ output}}{\eta_{PV\ yearly}}\right) \qquad \text{[GWhrs] (31)}$$

Where,

$$\eta_{PV\ yearly} = \eta_0 * (1-d)^n \qquad \text{[\%] (32)}$$

Where η_0 is the initial energy efficiency of the PV system, d is the degradation rate in %/yr and n is the years of operation. The energy efficiency of the PV system ranges from 5.25 – 16.13%, with a realistic value being 9.83%[37,48,49,59,82,86,91,95], which is rather conservative. More detailed information can be found in Table 8. The U.S. average solar irradiation of 15,000 GWh/ha-yr provides the required energy input. The degradation rate ranged from 0.35 – 0.8%/yr with a realistic average of 0.49%/yr[57,58,90]. Jordan [58] looked at over 10,000 samples and identified over 2000 high quality samples (high quality based on the following criteria: multiple measurements were taken for increased confidence; the measurement methods and calibrations were clearly described and are generally similar at each measurement point; details on the installation (disregarding proprietary considerations) are provided.

Table 8: Module and system efficiencies for PV used in this study.

Source	**PV Energy Efficiencies**	**PR**		**System**
[91]	11.94%	0.75		8.96%
	13.20%	0.75		9.90%
	7.00%	0.75		5.25%
	12.00%	0.75		9.00%
[59]	9.00%	0.75		6.75%
	14.00%	0.75		10.50%
[95]				
	12.80%	0.75		9.60%

	12.80%	0.75		9.60%
	15.80%	0.75		11.85%
[37]	12.40%	0.75		9.30%
[86]	12.80%	0.78		9.98%
	10.70%	0.8		8.56%
	13.20%	0.75		9.90%
	12.90%	0.75		9.68%
	14.00%	0.75		10.50%
[49]	12.30%	0.8		9.84%
[48]	15.50%	0.75		11.63%
[82]	21.50%	0.75		16.13%

The nameplate capacities are 5.23 GW for PVs1 and 12.13 GW for PVs2[106]. These were determined using SAM. The location of Huron, South Dakota was chosen for its average solar insolation, similar to the data gathered from literature. A simple efficiency module was used with an SMA America SC750CP-US inverter. A parametric analysis was performed to find the most optimal tilt angle of 37 degrees. Another parametric analysis was performed to find the correct nameplate capacity that gave the desired electrical output for PVs1 and PVs2. SAM assumes a 25 year lifetime so excel was used to continue the trend shown in SAM for degradation rates for each remaining year of the lifetime.

The GHG emissions released to the atmosphere during operation, $\pi_{PV\ operation}$, are 8.69x10^4 and 1.98x10^5 t_{CO2eq} for PVs1 and PVs2, respectively and calculated by equation 33:

$$\pi_{PV\ operation} = \alpha_{PV\ operation} * \frac{\beta_{out}}{\delta} \qquad [t_{CO2eq}]\ (33)$$

A range of 0-46.3 t_{CO2eq}/GWh_{out}[112] are emitted during installation of a PV farm due to biomass removal and subsequent soil respiration. The worst case assumes locating a PV farm in a heavily forested area with CO_2 emissions from loss of forest sequestration, soil respiration and oxidation of cut biomass. An assumption of 0.46 t_{CO2}/GWh (1% of maximum) from deforestation was employed for this study as forests are not typically clear cut for PV farms. Resulting in 8.69x10^4 t_{CO2} being emitted from the location of the PV farm from vegetation clearing and soil respiration[32].

Land transformation due to the PV farm, $A_{PV\ operation}$, are 11.96 and 22.41 kha for PVs1 and PVs2, respectively and are calculated as the average of equations 34 and 35 as well as data from SAM:

$$A_{PV\ operation} = \tau^*_{PV\ operation} * C_{NP} \qquad [kha]\ (34)$$

$$A_{PV\ operation} = \tau_{PV\ operation} * \beta_{out} \qquad [kha]\ (35)$$

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/GW[112], 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 3.78 kha/GW[76,78,92]. 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}[35]. These were multiplied by nameplate capacity or lifetime exergy output and then averaged together to determine the final values. From SAM, the modules alone have a physical footprint of 4.4 kha and 10.03 kha while the entire array will occupy 10.93 and 25.07 kha for PVs1 and PVs2, respectively. These were also averaged in to find the realistic values given above. The land transformation ranged from 3.70 – 19.80 kha for PVs1 and 7.02 – 39.31 kha for PVs2.

7.2.3 Downstream

The energy input from solar irradiation for bio-sequestration is 6.87×10^{6} and 1.37×10^{7} GWhrs with total GHG emissions to be offset with bio-sequestration equating to 1.01×10^{7} and 2.01×10^{7} t_{CO2eq} which transforms 9.16 and 18.27 kha of land[37,95,108,112] for PVs1 and PVs2, respectively. Total land transformation over the complete life cycle is 21.70 and 41.78 kha for PVs1 and PVs2.

Solar incidence on the land required for bio-sequestration accounts for the total energy into this phase of the analysis. The energy inputs, $\beta_{PV\ bio}$, are 6.87×10^{6} and 1.37×10^{7} GWh for PVs1 and PVs2, respectively are calculated with equation 36 and 37:

$$\beta_{PV\ bio} = G * N * A_{PV\ bio} \qquad \text{[GWhrs] (36)}$$

Where,

$$A_{PV\ bio} = \frac{(\alpha_{PV\ upstream} + \alpha_{PV\ operation}) * \beta_{yearly\ output} * \sigma}{\omega} \qquad \text{[kha] (37)}$$

Switchgrass offers the best carbon sequestration potential of 6 t_C/ha-yr[64] and sequesters enough carbon to offset the CO_{2eq} released by the implementation of the PV farm. The sequestration potentials of various forms of biomass can be seen in Table 9. Switchgrass, among others, has been shown to sequester carbon steadily for over 50 years with little maintenance[88].

Table 9: Carbon uptake rates of various types of biomass.

Biomass Type	Value (tC/ha*yr)
Switchgrass	6.0[64]
Poplar	5.4[64]
Willow	4.3[64]
Woody Tissue	3.8[80]

Average US Forest	0.7[31]

The total emissions from PV to be sequestered by biomass, $\pi_{PV\ bio}$, are 1.01x10^7 and 2.01x10^7 t_{CO2eq} for PVs1 and PVs2 respectively, are calculated by equation 38:

$$\pi_{PV\ bio} = \pi_{upstream} + \pi_{operation} \qquad [t_{CO2eq}]\ (38)$$

The total GHG emissions that require bio-sequestration range between 1.97x10^6 – 5.08x10^7 t_{CO2eq} for PVs1 and 3.24x10^6 – 9.46x10^7 t_{CO2eq} for PVs2. This large range is due mostly to the variety of studies aggregated from the literature. While a focus was put on using studies made in the last 10 years due to the fast pace innovation of PV, with moderate solar insolation between 1400 and 1700, multi-crystalline silicon cells, and performance ratio's between 0.70-0.85; these ranges ultimately compound to create a large spread of values.

A detailed breakdown of the life cycles of PVs1 for energy flow, emissions and land transformation can be seen in Table 10. The same for PVs2 can be seen in Table 11.

Table 10: Overview of energy flow, emissions and land transformation by life cycle phase in a climate neutral PV farm outputting 376 TWhrs of electricity over the lifetime (PVs1).

Life Cycle Phase	Source/ Sink	$Energy_{in}$ (GWh)	$Energy_{out}$ (GWh)	Emissions (t_{CO2eq})*	Land Transformation (ha)
PVs1 Upstream	Modules	1.25x10^4 95,37,4,86,5,48		3.89x10^6 112,95,37,4,36,103,86,48,49	4.15x10^2 35
	BOS	7.36x10^3 95,37,4,86,5,48		6.10x10^6 112,95,37,4,36,103,86,48,49	1.69x10^2 35
	Construction	7.16x10^1 96,107		1.32x10^5 96,107	N/A
	Total	2.00x10^4 95,37,4,86,5,48,96,107		9.99x10^6 112,95,37,4,36,103,86,48,49,96,107	5.84x10^2 35
PVs1 Operation	PV Farm	4.30x10^5 95,37,59,42,58,82,90,91,57,86,48,49	3.76x10^5	8.69x10^6 112	1.20x10^4 112,35,110,76,92,106
PVs1 Downstream	Bio-Sequestration	6.87x10^6 112,95,37,36,103,118,64,88		-1.01x10^7 112,96,95,37,107,36,103,86,48,49	9.16x10^3 112,95,37,36,103,63

*carbon sequestration as negative and carbon equivalent emissions as a positive numbers.

Table 11: Overview of energy flow, emissions and land transformation by life cycle phase in a climate neutral PV farm outputting 866 TWhrs of electricity over the lifetime (PVs2).

Life Cycle Phase	Source/ Sink	$Energy_{in}$ (GWh)	$Energy_{out}$ (GWh)	Emissions (t_{CO2eq})*	Land Transformation (ha)
PVs2 Upstream	Modules	$2.89x10^4$ [95,37,4,86,5,48]		$7.74x10^6$ [112,95,37,4,36,103,86,48,49]	$7.88x10^2$ [35]
	BOS	$1.70x10^4$ [95,37,4,86,5,48]		$1.22x10^7$ [112,95,37,4,36,103,86,48,49]	$3.21x10^2$ [35]
	Construction	$1.43x10^2$ [96,107]		$3.06x10^6$ [96,107]	N/A
	Total	$4.60x10^4$ [95,37,4,86,5,48,96,107]		$1.99x10^7$ [112,95,37,4,36,103,86,48,49,96,107]	$1.11x10^3$ [35]
PVs2 Operation	PV Farm	$9.91x10^6$ [95,37,59,42,58,82,90,91,57,86,48,49]	$8.66x10^5$	$1.98x10^5$ [112]	$2.24x10^4$ [112,35,110,76,92,106]
PVs2 Downstream	Bio-sequestration	$1.37x10^7$ [112,95,37,36,103,118,64,88]		$-2.01x10^7$ [112,96,95,37,107,36,103,86,48,49]	$1.83x10^4$ [112,95,37,36,103,63]

*carbon sequestration as negative and carbon equivalent emissions as a positive numbers.

8. Energy Comparison

The energy analysis includes the inputs from solar irradiation and the heat content of coal, as well as electricity, diesel and other upstream sources used to produce electricity to create a complete LCA. With these factored in, the energy 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 Figure 2a. This is true for all PV and coal scenarios.

The realistic value for the energy penalty when using CCS is 26%. Compared with Coals1, CCS reduces the solar energy required for bio-sequestration 3.06 times less Coals2a and 1.20 times less for Coals2b. The total energy input for PVs1 is 23 times lower than Coals1 and nearly 8 times lower than Coals2a, as illustrated in Figure 2a. PVs2 has a total energy input that is 9 times lower than Coals2b, as illustrated in Figure 2b. The increased energy input to upstream and operational phases for coal fired plants with CCS is negated by the solar energy required for bio-sequestration for Coals1. In general, the total energy input is driven by the solar irradiation for bio-sequestration. The error bars represent the minimum and maximum values found in literature for the life cycle phase of each scenario. In general, PV has a larger range of values, presumably because of the effect of weather variations between studies and rapid rate of improvements in technology compared to coal.

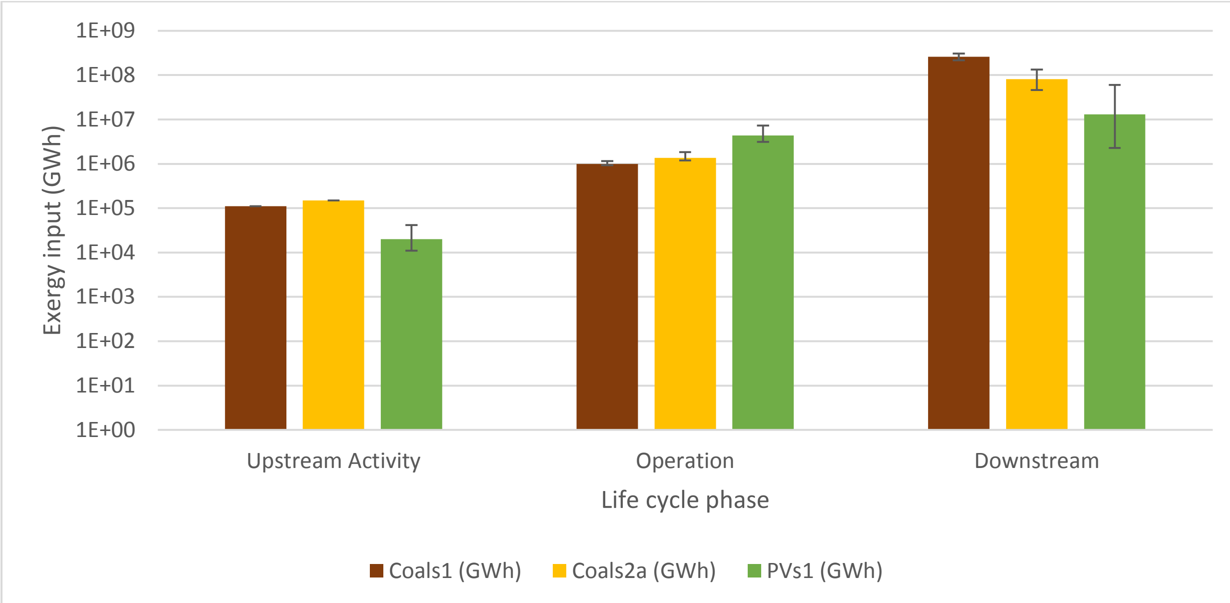

Figure 2a: Lifetime energy input by life cycle phase comparing Coals1, Coals2a and PVs1, each outputting 376 TWhrs.

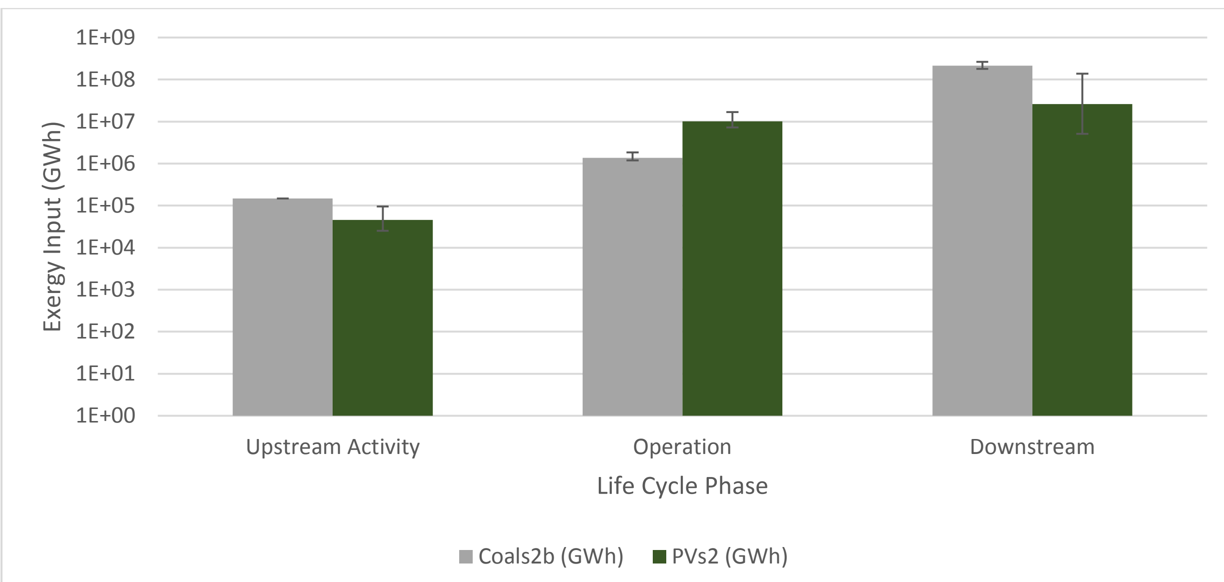

Figure 2b: Lifetime energy input by life cycle phase comparing Coals2b and PVs2, outputting 866 TWhrs.

For the upstream energy inputs that emit GHG emissions, Coals1 and Coals2a require 8.83×10^4 and 1.17×10^5 GWhrs more than PVs1. This is 5.42 and 6.85 times more. Coals2b requires 9.08×10^4 GWhrs more than PVs2, which is 2.98 times more. But when looking at GHG emitting energy inputs over the whole life cycle, Coals2a increases to 1.45×10^5 GWhrs, making it 8.25 times more than PVs1 and Coals2b increases to 2.01×10^6, making it 44.71 times more than PVs2. The use of EOR greatly increases the use GHG emitting activities. Figure 3a shows that when you focus on carbon emitting activities (exclude the energy input from solar irradiation and the heat content of coal), coal requires significantly more energy than PV over its life cycle. Figure 3b shows how coal also requires more energy input per GWh_{out} than PV.

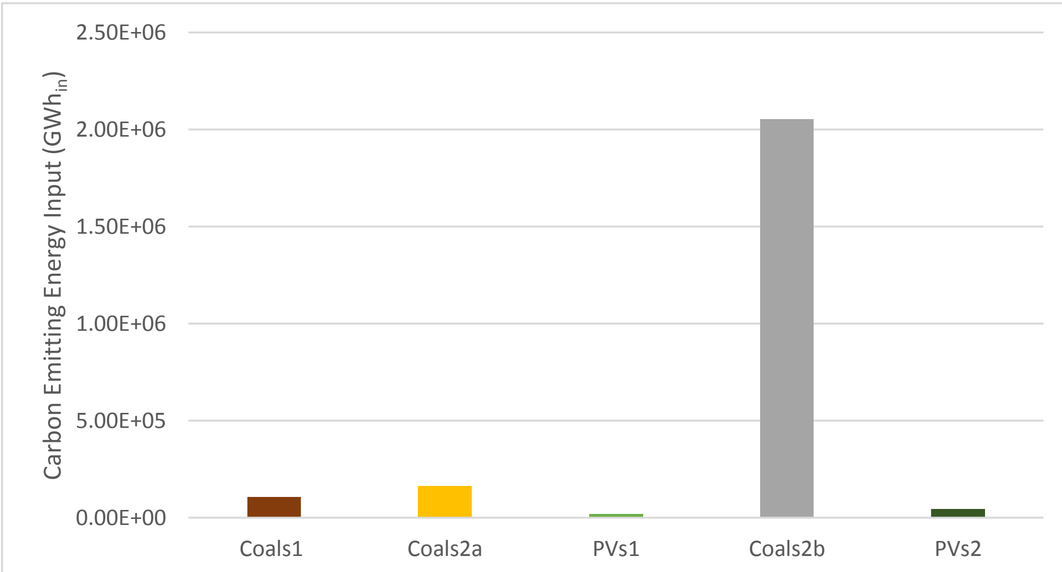

Figure 3a: The total life cycle energy input for carbon emitting processes for all coal and PV scenario's.

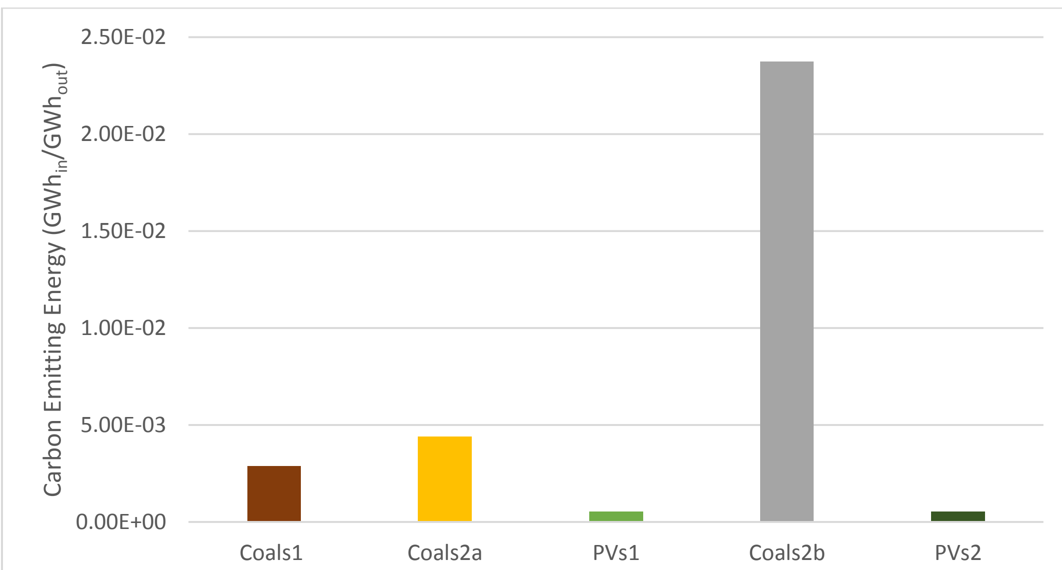

Figure 3b: The total life cycle energy input for carbon emitting processes per GWh_{out} for all coal and PV scenario's.

9. GHG Emissions Comparison

PVs1 will emit between 1.50 – 47.75 Mt_{CO2eq} with a realistic value of 10.08 Mt_{CO2eq} to the atmosphere[36,37,95,103,112,115]. This range is primarily driven by the range in upstream emissions but the assumption of 1% of maximum used for emissions during operations play a large role as well. Coals2a emits between 67.78 – 168.90 Mt_{CO2eq} with a realistic value of 123.40 Mt_{CO2eq} to the atmosphere, which is over 12x more. Coals1 emits the most with a range between 319.05 – 475.59 Mt_{CO2eq} and a realistic value of 379.11 Mt_{CO2eq}, over 37x more than, is released to the atmosphere, as seen in Figure 4a[2,8,56,68,96]. Coals2b will emit 298.24 – 386.35 Mt_{CO2eq} with a realistic value of 316.55 Mt_{CO2eq}[8,56,68,96]. By comparison, PVs2 produces 3.24 – 94.63 Mt_{CO2eq} with a realistic value of 20.10 Mt_{CO2eq}, over 15x less, as seen in Figure 4b[37,95,112].

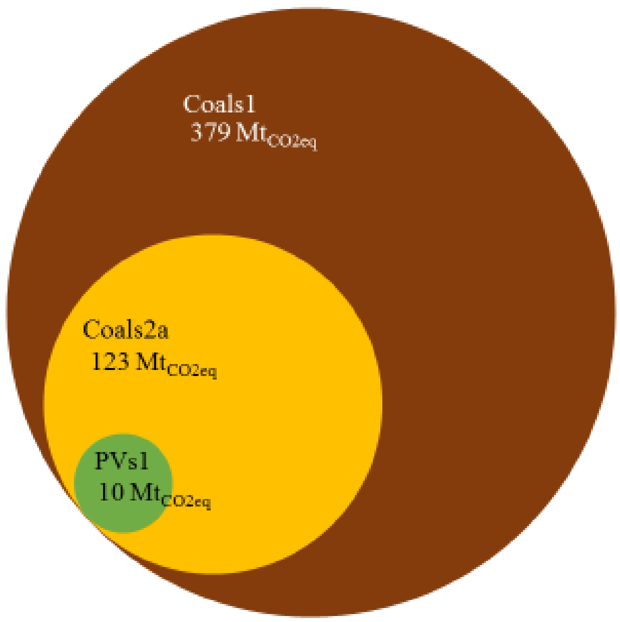

Figure 4a: Comparing LCA GHG emissions from Coals1, Coals2a and PVs1. All use bio-sequestration to fully or partially sequester CO_2 and all output 376 TWhrs of electricity.

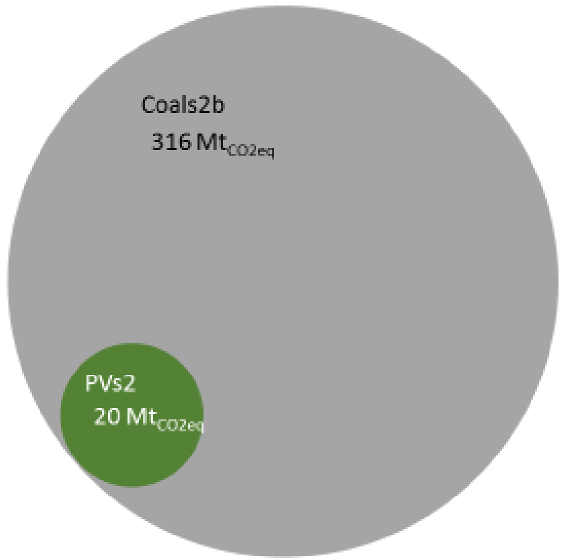

Figure 4b: Total LCA GHG emissions from Coals2b and PVs2. Both use bio-sequestration to fully or partially sequester CO_2 and both net output 866 TWhrs of electricity over their lifetime.

CCS has been shown to decrease global warming potential by 63-82% and EOR has been shown to have a global warming potential of 1.8 times higher than CCS that doesn't utilize CO_2 and 2.3 times lower than coal fired plants without CCS[39]. Different studies shown EOR with a global warming potential at 3.7 to 4.7 times higher than a coal plant without CCS[56]. This study shows it to be 2.7 times higher.

The energy penalty from CCS is made up for by a significant decrease in emissions released to the atmosphere during operation, as seen in Figure 5a. 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[30], which the author believes has prompted companies to report zero leakage and hindered efforts for more accurate studies.

Over their life cycles, the combustion of refined oil product is less polluting than coal, but compared to PVs2, it is still significantly more polluting, as seen in Figure 5b.

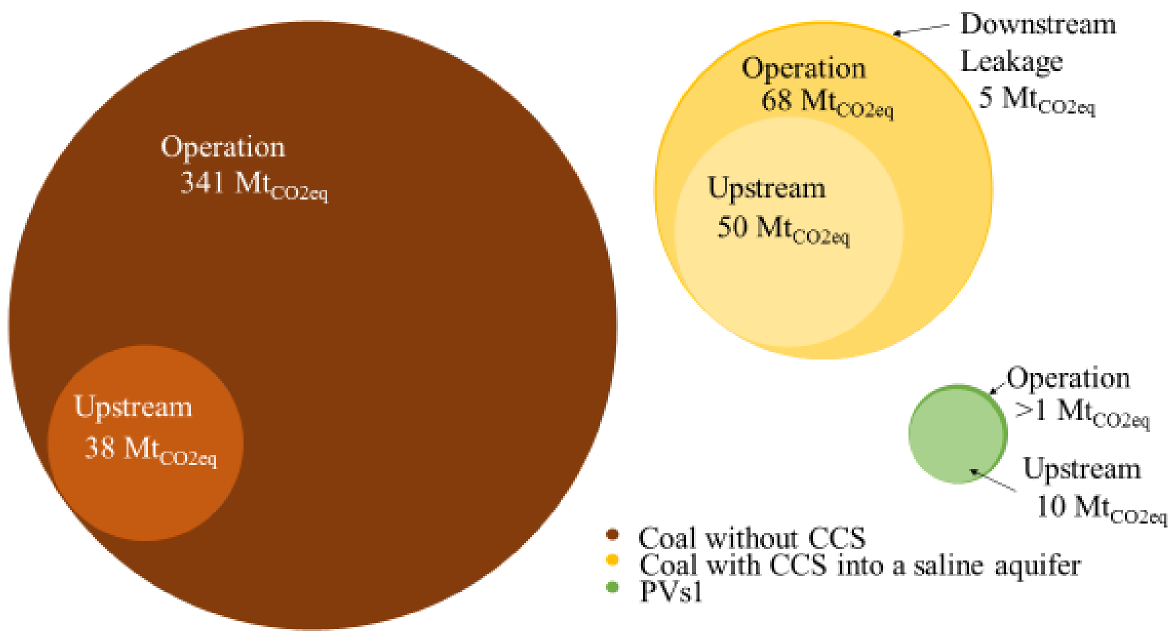

Figure 5a: To-scale visualization of GHG emissions by life cycle phase for Coals1, Coals2a and PVs1, each outputting 376 TWhrs of electricity over their lifetimes.

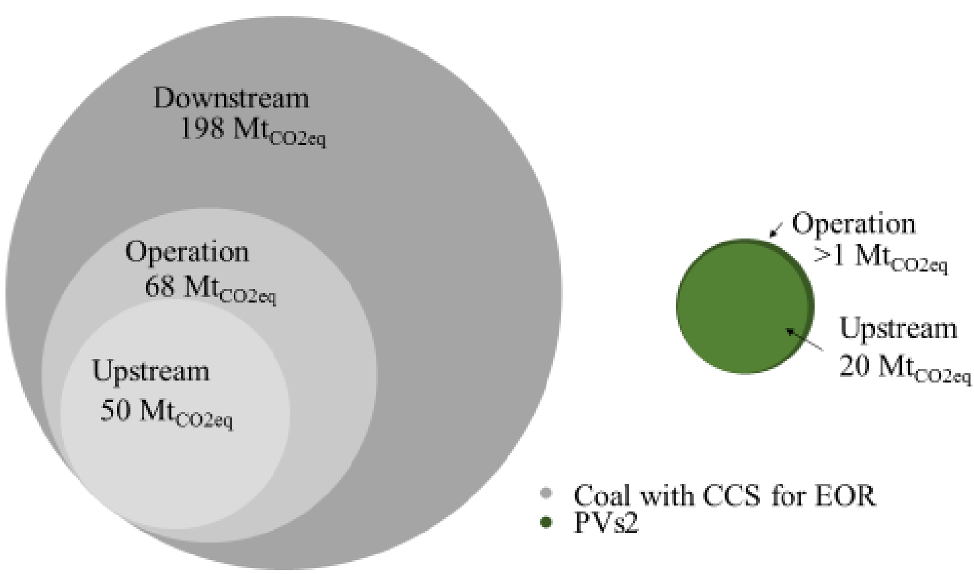

Figure 5b: To-scale visualization of GHG emissions by life cycle phase for Coals2b and PVs2, each outputting 866 TWhrs of electricity over their lifetimes.

To compare all coal and PV scenario's global warming potentials, they were charted on a per GWh_{out} basis. Coals1, Coals2a, Coals2b, PVs1 and PVs2 emit 1004.23 t_{CO2eq}/GWh_{out}, 313.17 t_{CO2eq}/GWh_{out}, 358.56 t_{CO2eq}/GWh_{out} and 23.99 t_{CO2eq}/GWh_{out}, respectively. As seen in Figure 6. Coal without CCS and PV have similar numbers to those posted by the IPCC. The utilization of CO_2 for EOR is slightly worse than strictly storing the CO_2 in saline aquifers, from an emissions standpoint.

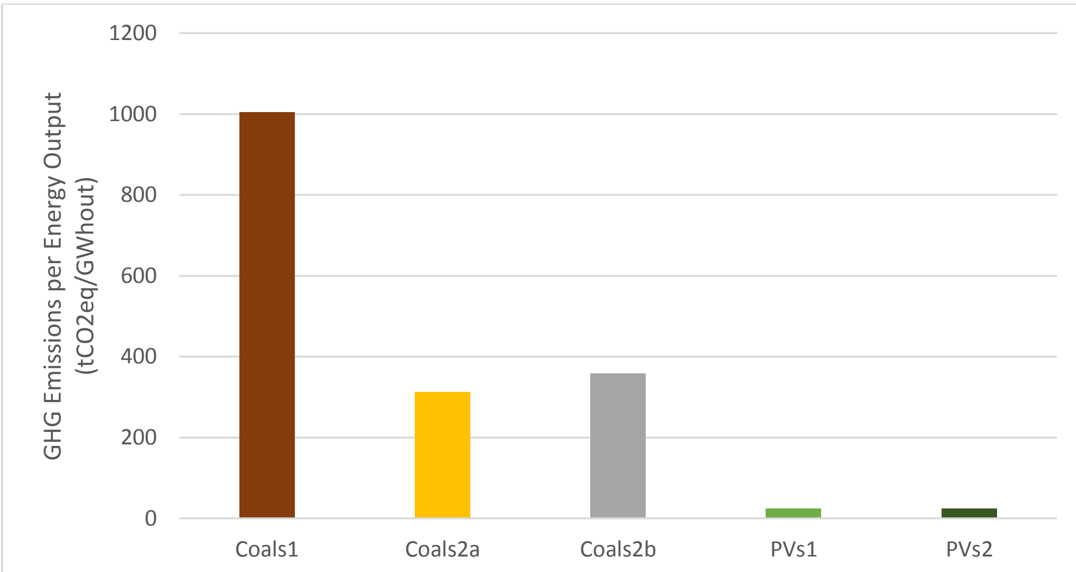

Figure 6: All coal and PV scenario's GHG emissions on a per GWh_{out} basis.

10. Land transformation Comparison

The amount of land transformed by PVs1 is over 16x less than for Coals1. The use of CCS into a saline aquifer helps reduce emissions to the atmosphere and drops land transformation from Coals2a, but it is still 5x more than PVs1, as seen in Figure 7a. Coals2b requires 7x more land transformation than PVs2 because the increase in electrical production is offset by the combustion of oil, as seen in Figure 7b. The land transformation for the EOR process was not included so these numbers are considered conservative.

The majority of land transformation for both PV and coal is for bio-sequestration. For Coals1, Coals2a and Coals2b, 81 – 95% of the total land transformation in its life cycle is for bio-sequestration, while it is 76% and 78% for PVs1 and PVs2, respectively. For reference, 344 kha of land is transformed for bio-sequestration in Coals1, which is larger than the state of Rhode Island. The total land area of the continental U.S is 9.15×10^8 ha, with agriculture accounting for 44.5%, arable land at 16.8% and forest area at 33.3% of the total[12]. If all emissions from coal-fired electricity power generation in the United States were bio-sequestered with switchgrass, it would require 61% of the arable land in the U.S.[11]. With CCS into a saline aquifer, it would still require 19% of the arable land in the U.S. to be planted with switchgrass to bio-sequester the whole fleet[11].

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 required[31], resulting in a new forest occupying an area larger than the state of Maryland for Coals1. To bio-sequester the whole fleet of U.S coal plants then a new forest would have to be 2.64 times larger than the existing forest area in the U.S. This is the same as requiring a new forest that covers 88.50% of the total area of the entire U.S.[11]. If CCS into a saline aquifer were utilized, a new forest with an area that is 85.72% of the existing forest in the United States is required[11].

In contrast, if all electricity generation from coal were replaced by climate neutral PV, then bio-sequestration with switchgrass would require 4% of the arable land in the U.S. If it were bio-sequestered with the average U.S. forest then it would require 5% of the total area of the U.S., or a new forest that is 5% as big as the existing forest currently in the U.S.

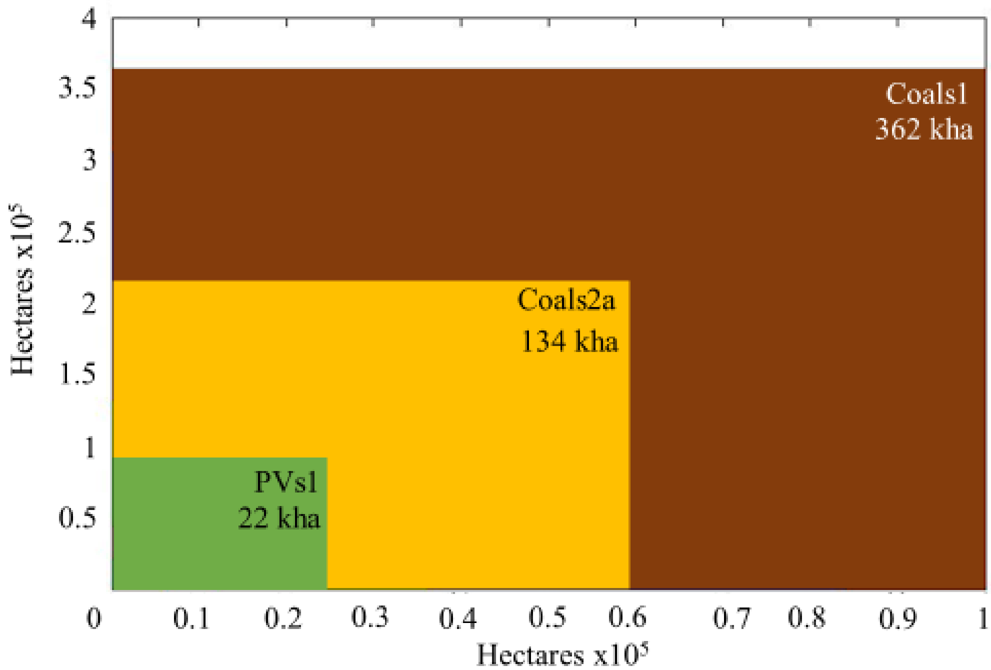

Figure 7a: Total land transformation required for Coals1, Coals2a and PVs1, each producing 3.76×10^8 GWhrs electricity over their lifetime. Shown to scale relative to each other.

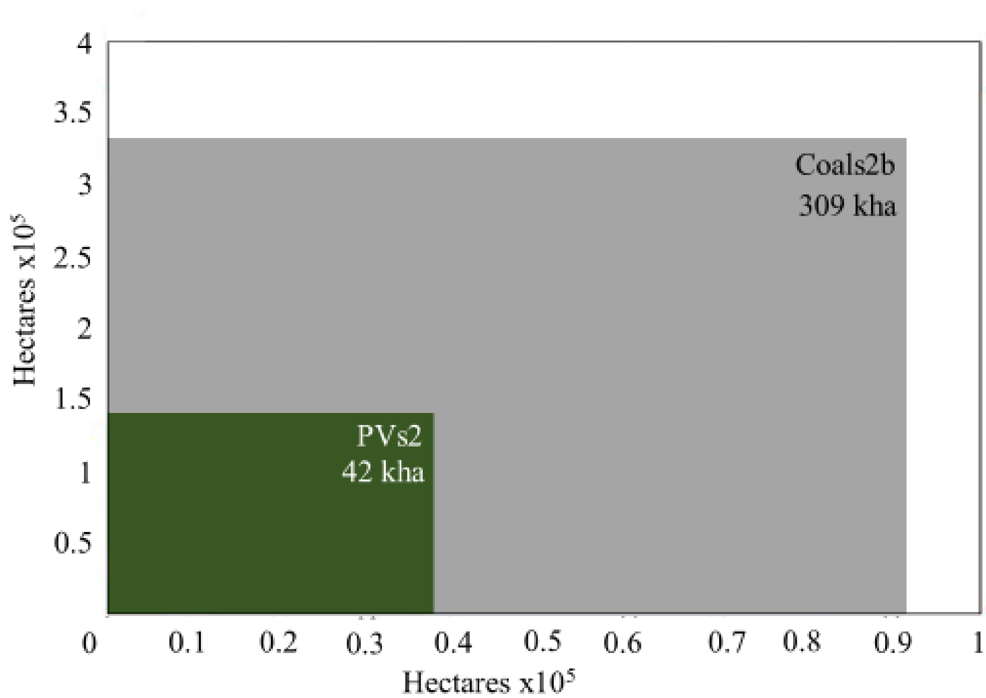

Figure 7b: Total land transformation required for Coals2b and PVs2, both producing 866 TWhrs electricity over their lifetime. Shown to scale relative to each other.

In western US, 97 kha of federal land were approved or pending for utility scale solar and over 18 Mha were considered suitable (mainly shrubland). Utility scale is defined as > 20MW. In California alone, 86 kha of land are operating or under construction or planned for utility scale solar. The Mojave desert has 220 kha of pending applications at the BLM[44].

Land transformation for equivalently sized coal and PV installations can be seen in Figures 5a & 5b, but land transformation on a per t_{CO2eq} basis is also useful. These values are $9.57x10^{-4}$, $1.12x10^{-3}$, $9.88x10^{-4}$, $2.41x10^{-3}$ and $2.60x10^{-3}$ for Coals1, Coals2a, Coals2b, PVs1 and PVs2, respectively.

Land transformation excluding bio-sequestration and assuming no new pipeline infrastructure is 4.53 kha, 17.52 kha and 21.73 kha for PVs1, Coals1 and Coals2a. It is 10.27 kha and 23.33 kha for PVs2 and Coals2b. This study does not include the land transformation from oil extraction but estimates with incomplete life cycles have put it at 20.7 million acres with potentially up to 50 million acres[44].

11. 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 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.

Recent advances have made CCS more feasible, and in conjunction with EOR more practical. However, the economics for CCS have gotten worse, not better in the years after the watershed report from the IPCC[28]. Most CCS projects involve EOR to be viable and many planned projects w/o EOR are being cancelled[84]. Moreover, the process of EOR only sequesters 28% of the CO_2 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.

In 2009, it was claimed that when solar insolation is 1800 kWh/m^2/yr, PV can produce the same amount of electricity as coal given the same land. But it is proven here that when both are climate neutral, then PV is the clear winner at average solar insolations.

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 energy, GHG emissions and land transformation perspective, by several orders of magnitude each. 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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13. Appendices

Appendix A

Table A1: Coal mining land transformation from the annual coal reports from the OSMRE, years 2002 to 2012[34]

Coal Mining Land Transformation (acres)			
Year	New Permitted Acreage	Phase III Bond Release	Reclaimed
2002	115926	73407	8019
2003	113714	60641	6539

2004	116805	50084	6985
2005	80569	52479	6533
2006	191638	49477	6984
2007	211614	48914	6658
2008	152712	48828	9909
2009	212878	38312	5838
2010	174862	50231	16565
2011	158107	35334	10836
2012	179426	44985	17821
Avg	155295.5455	50244.72727	9335.181818
Avg Net Total Increase per year	95715.63636		

Appendix B: Detailed information on EOR productivity and leakage rates

Table B1[31]

EOR		
kgCO_2 in an scfCO2$_2$	0.05189	
incrementally more output from EOR	280000	bbl/day
total oil produced from EOR	5.1	%
original oil retrieved by EOR	10-20	%
original oil retrieved by primary	5-15	%
original oil retrieved by secondary	20-40	%
volume used per day by EOR	3000000000	scfCO2
volume	10700	scfCO2/barrel of oil
mass	155462.44	tonsCO2/day
mass	0.43	tonCO2/barrel of oil

incremental mass emitted by EOR through oil combustion	120400	tonsCO2/day

Table B2[37]

Total US CO2 consumed for EOR	50	MMTCO2
Top 5 Natural sources of CO2	5130	MMTCO2
Oil Extraction emissions	9	gCO2eq/MJoil
	0.3771	tCO2eq/tOil
Oil Refining emissions	0.05	tCO2eq/bbl
Refined Oil Combustion Emissions	0.394	MMTCO2eq/bbl
Based on these 5 large scale cases, 3.7-4.7x more CO2 emitted than sequestered		
US LCA emissions for oil	530	kgCO2eq/bbl

Table B3[86]

Weyburn Case:		
CO2 Injected	95	million ft^3/day
Additional Oil Recovered	130	million barrels total
Estimated CO2 sequestered	30	MMTCO2
Montana Elm Coulee & Cedar Creek:		
Estimated CO2 Sequestered	109	MMTCO2
Estimated Additional Oil	666	million barrels total
Total Sequestration Potential in US	138	BMTCO2
ARI prediction:		
EOR Sequestration Capacity to 2030	7.5	BMTCO2
EOR Additional Oil Recovered to 2030	39	billion barrels oil
	48	billion barrels oil
Estimated Percent Sequestered	-1.236	%
	-1.752	%
Leakage Rate	0.00001	%

Table B4[102]

Salt Creek Case:		
Length of pipeline	254	km
Additional Oil Recovered	8000	barrels/day
CO2 sequestered	125	million scf/day

Table B5[75]

Sleipner Case:		
Stored CO2	0.546875	% of injected
Stored CO2	35	MtCO2
Oil Extraction emissions, w/o EOR	180	kgCO2eq/m^3 oil
Oil Extraction emissions, w/ EOR	128	kgCO2eq/m^3 oil
Oil Produced w/o EOR	44.31	Mm^3
Oil Produced w/ EOR	18	Mm^3

Table B6[90]

80% of CO2 for EOR comes from natural sources		
estimates additional oil production	5.5	kgCO2/kg oil out
43% comes from recycling plant		
Recycling Plant emissions	0.36	kgCO2/kg oil out
	0.0015	kgCH4/kg oil out
	0.000021	kgN2O/kg oil out
	0.4038	
Storage capacity	2.6	kgCO2/kg oil out
Car combustion emissions	4.5	kgCO2eq/kg gasoline

Table B7[76]

CO2 used for EOR	48	Mtons
additional oil produced from EOR	280000	bbl/day

Table B8[113]

Weyburn Case		
Recycle Process Leakage	6	%
Crude oil CO2 intensity	0.16	tCO2/m^3
CO2 compression leakage	13	%
Crude Oil refining emissions	0.0253	tCO2eq/bbl
Oil Combustion emissions (avg)	2.96	tCO2eq/m^3

Table B9[40]

EOR extraction leakage	13.7	% of total injected
Recycling (% of total extraction)	11	%
Vented CO2 (% of total extraction)	38	%
Vented CH4 (% of total extration)	42	%

Crude Oil Transport	0.004	tCO2/bbl
Crude Oil Refining	0.03	tCO2/bbl
Refined Product Combustion	0.431	tCO2/bbl

Table B10[57]

Injection Leakage	10	% of total