RESOURCE IMPLICATIONS OF A FORESTRY BASED FISCHER-TROPSCH SYNTHESIS SYSTEM WITH CARBON CAPTURE AND STORAGE IN THE SOUTHEAST, USA

by

JAMES JOHN BALE JR.

(Under the Direction of John R. Schramski)

ABSTRACT

Continued growth in anthropogenic greenhouse gas emissions necessitate the development of techniques and technologies, which enable deep reductions in future emissions from human activity. Modeling scenarios consistent with limiting planetary warming below 2 ^{o}C by the end of the century require large scale deployment of negative emission technologies (NETs) which remove carbon dioxide from the atmosphere. Bioenergy with carbon capture and storage (BECCS) is one NET widely assumed to provide necessary carbon removal while also providing energy. This study estimates the land, water, and energy impact of generating negative emissions via Fischer-Tropsch synthesis with pre-combustion carbon capture and storage (FT-CCS) using forest biomass from loblolly pine plantations under conditions typical in the southeastern United States. Forestry based FT-CCS was found to have a lower water footprint, provide less energy, and require much greater land use than alternative BECCS systems evaluated in previous estimates from the literature.

INDEX WORDS: Bioenergy with carbon capture and storage, BECCS, Fischer-Tropsch synthesis, Forest bioenergy, Negative emission technology, Climate change, Resource constraints.

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DEDICATION

I would like to dedicate this thesis to my parents who have always been such an incredible source of guidance, love and support.

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CHAPTER 1

Introduction

The onset of climate change from anthropogenic emissions is likely to worsen given that annual CO_2 emissions have continued to rise exponentially since the dawn of the industrial era. Annual global emissions from anthropogenic sources climbed to ~40.8 Gt CO_2 in 2016 [1]. Future rates of planetary warming will depend heavily on cumulative CO_2 emissions released from human activity along with complex geophysical and ecological responses from an appreciably altered planetary carbon cycle [2]. Humans are rapidly burning through the remaining carbon budgets quantified in the 2015 Paris Agreement [3, 4]. A number of studies have highlighted the need for greenhouse gas (GHG) mitigation tools, particularly negative emission technologies (NETs), to prevent overshoot of the remaining carbon budgets consistent with stabilizing planetary temperatures below $2^{o}C$ above pre-industrial conditions [5-7].

NETs are a suite of climate mitigation technologies including afforestation/reforestation, biochar, soil carbon sequestration, direct air capture (DAC) and bioenergy with carbon capture (BECCS) whose deployment results in a net removal of greenhouse gasses from the atmosphere [8]. Bioenergy with carbon capture and storage (BECCS) is one such example of an NET, assumed to deliver negative emissions in the future through the combination of sustainably harvested biomass for energy use with carbon capture and storage (CCS). Modeling scenarios consistent with a 66% likelihood of stabilizing average planetary temperatures below 2 ^{o}C increase relative to pre-industrial conditions in 2100 assume median deployment of BECCS at a rate of 3.3 GtC removed per year [7]. While BECCS potentially provides a promising suite of technologies that enable emission reductions, deployment has been slow and the climate mitigation potential remains inconsequential [9]. Currently, there is only one demonstration scale BECCS plant operating globally, a corn-to-ethanol fermentation plant in Decatur, Illinois that injects CO_2 into the Mount Simon Sandstone reservoir at a rate of 0.9 $MtCO_2$/year [10]. The gap between needed NET deployment and current development highlights the challenge for the global engineering community to rapidly develop and commercialize technologies that result in GHG removal. A challenge that remains exceedingly complex given the scale of emission reductions required and the incredible demand for energy human civilization exerts on the biosphere.

Additionally, there are a number of different conversion technologies suitable for production of both bioelectricity and biofuel, each with different opportunities and challenges for incorporating CCS. BECCS will require substantial allocation of extant resources by way of land, water, and nutrients at gigatonne deployment scales. Given the aforementioned goals for climate mitigation [4-7] and the variable options for commercializing BECCS, a quantitative assessment of environmental impact and total sequestration capabilities of variable BECCS technologies is needed.

This study seeks to investigate the resource impacts associated with BECCS deployment via Fischer-Tropsch synthesis with pre-combustion carbon capture and storage to generate long chain hydrocarbon fuels to potentially replace diesel and gasoline. Woody biomass from loblolly pine grown under conditions typical to plantation silviculture in the southeastern U.S is used for biomass feedstock. Consideration is also given to systems in which coal and biomass are co-utilized for fuel production. The land-use intensity, water consumption, and energy generation associated with the negative emission potential of this BECCS system are estimated. The objectives of this project are to:

1. Develop a whole system carbon accounting model of FT-CCS in Excel, drawing from a variety of sources found in the literature.

2. Estimate the greenhouse gas, land, energy, and water impacts associated with FT-CCS deployment using forest residues and a portion of pulpwood from loblolly pine as a feedstock under typical existing management practices for softwood plantations in the Southeastern United States.

3. Explore how co-utilization of coal affects the production capacity and emission profile of FT fuels.

Chapter 2

Background and Literature Review

2.1 Carbon Budgets

The Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) functions to support the United Nations Framework Convention for Climate Change (UNFCCC) by providing policy recommendations and serves as the foundation for the Paris Agreement, which aims to maintain global temperature rise below 2^{o}C as measured from pre-industrial times to the end of the 21st century [2, 3, 5]. Working Group I provides the physical science basis for understanding climate change and future warming scenarios. AR5 articulates four scenarios for analyzing future warming through 2100 and beyond: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Their approximate radiative forcing (W/m^2) in year 2100 identifies these scenarios, known as Representative Concentration Pathways (RCPs), [11]. RCPs in the IPCC are generated using the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5), which incorporates a wide range of climate models of varying complexity. These RCPs are useful for analyzing and comparing different emission pathways and developing policy frameworks for meeting mitigation goals.

The transient climate response to cumulative carbon emissions (TCRE) is the rate of future warming as a function of cumulative emissions. The rate of future warming is linearly correlated with cumulative emissions across a range of climate models [12]. Theoretically, the radiative forcing per tonne of CO_2 emitted decreases as the total concentration of CO_2 increases. However, additional emissions further degrade the ability of oceanic and terrestrial ecosystems to act as sinks for excess atmospheric carbon which leads to a greater proportion of emitted carbon remaining in the atmosphere [4]. While all GHGs drive the total mean global temperature response, CO_2 dominates the temperature response, accounting for 64% of all additional radiative forcing since pre-industrial times, and 80% of additional radiative forcing from 2005 - 2011[2]. As such, the global mean surface temperature anomaly can be determined from cumulative carbon emissions associated with each RCP (Fig. 1). The surface temperature anomaly in 2100 relative to the preindustrial era is approximately 1.7°C, 2.5°C, 3.0°C, and 4.6°C for RCP2.6, RCP4.5, RCP6.0, and RCP8.5 respectively.

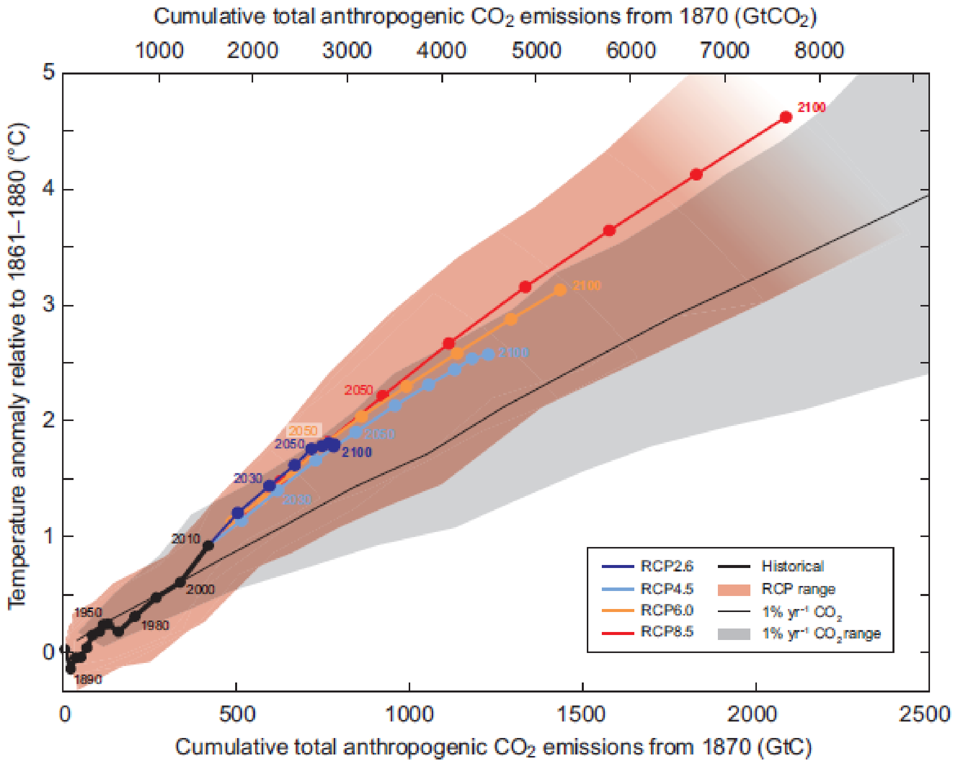
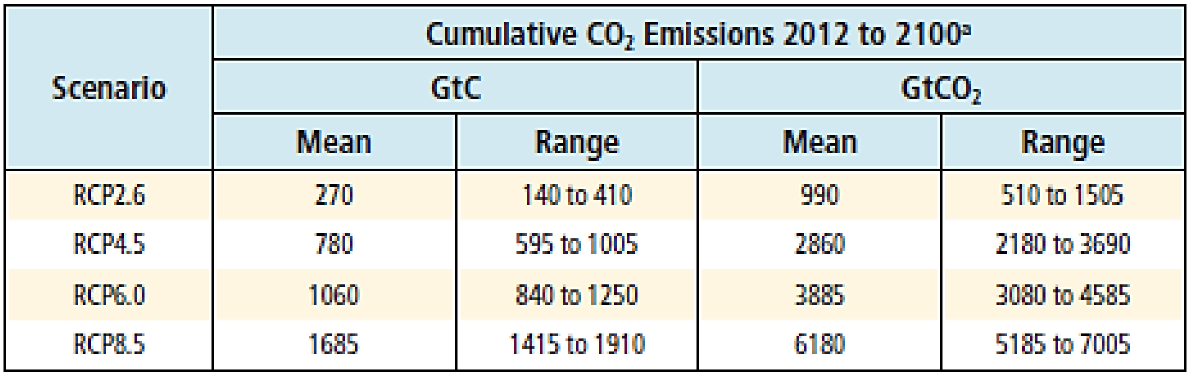


Figure 1: Global mean surface temperature increase as a function of cumulative total global CO_2 emissions for each RCP presented in IPCC AR5 Technical Summary [11]

TCRE serves as the foundation for estimating the cumulative carbon budgets associated with meeting climate stabilization goals and is a useful concept for determining the cumulative emissions associated with each temperature response (Table 1).

Table 1: Cumulative CO_2 emissions budget for the 2012 to 2100 period compatible with the RCP atmospheric concentrations simulated by the CMIP5 Earth Systems Models (1 GtC = 3.67 $GtCO_2$). [2]



Scenario	Cumulative CO_2 Emissions 2012 to 2100^{a}			
	GtC		$GtCO_2$	
	Mean	Range	Mean	Range
RCP2.6	270	140 to 410	990	510 to 1505
RCP4.5	780	595 to 1005	2860	2180 to 3690
RCP6.0	1060	840 to 1250	3885	3080 to 4585
RCP8.5	1685	1415 to 1910	6180	5185 to 7005

At the current rate of emissions, humanity will exhaust the 2^{o}C carbon budget in just 30 years [4]. For cumulative emissions less than 2000 GtC, the transient climate response is likely to be between 0.8 and 2.5^{o}C per 1000 GtC emitted [13]. If we limit planetary warming from anthropogenic emissions below 2^{o}C from preindustrial times, as suggested by the Paris agreement, then cumulative carbon emissions since the preindustrial era would likely have to remain below 1000 GtC. From 1880 to 2011 anthropogenic emissions have already accounted for 445 to 585 GtC of this budget. Accounting for past CO_2 emissions, the remaining carbon budget consistent with maintaining planetary temperatures below 2^{o}C (66% probability), is estimated to be 706 $GtCO_2$ with global annual emissions reaching at 40.8 $GtCO_2$ in 2016 [1, 14].

Integrated Assessment Models (IAMs) were used in the Mitigation of Climate Change contribution of Working Group III to AR5. The IPCC defines mitigation as human intervention to reduce the sources or enhance the sinks of greenhouse gasses. These IAMs utilize explicit assumptions about the social, economic and ecological factors driving climate change to provide policy makers with potential transformation pathways for mitigation through 2100 and beyond [5]. These mitigation pathways are often compared back to the RCPs presented in the contribution of WG I to AR5 in order to assess their effectiveness. There are over 1000 IAMs considered in AR5 representing a wide range of mitigation outcomes.

The majority of mitigation pathways consistent with keeping planetary warming below 2°C in 2100 involve temporary overshoot of GHG concentrations in the first half of the century with large scale deployment of net-negative emissions during the second half of the century[5]. In fact, some 87% of the IAM pathways associated with RCP2.6 and the stabilization of the climate below 2°C by 2100 require global net negative emissions by the second half of the century [6]. Of the negative emissions technologies considered, bioenergy with carbon capture (BECCS) is by far the most widely anticipated and expected technology to meet these goals. Beyond RCP2.6, BECCS continues to be significantly incorporated into IAMs associated with higher mitigation targets in RCP4.5 and RCP6.

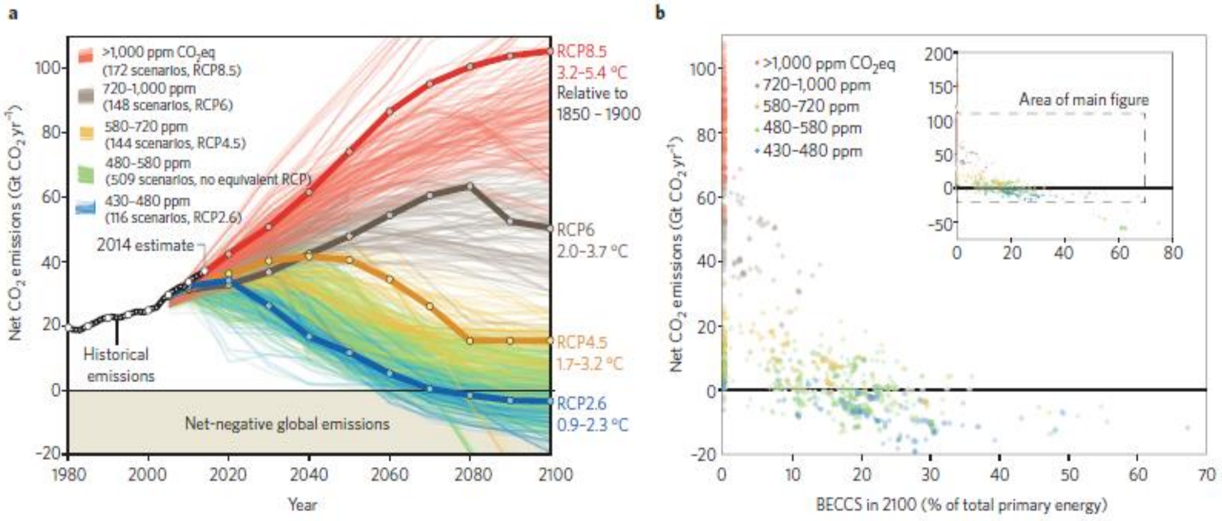


Figure 2: a) Carbon dioxide emissions pathways until 2100. Thick solid lines represent RCPs while thin lines represent IAMs b) Net CO_2 emissions in 2100 associated with each IAM and scale of BECCS deployment as a % of total primary energy.[6]

This reliance on BECCS and other negative emission technologies (NETs) within mitigation scenarios has generated controversy. BECCS and other NETs are not fully developed at commercial scale and the scale of deployment assumed in the mitigation scenarios is far greater than what is currently deployed. Additionally, the scale of deployment needed to make a significant contribution to mitigation could have drastic impacts on land use changes, competition for agriculture, and impacts on water; all of which require careful consideration before deployment is pursued [15]. Anderson and Peters argue that the inclusion of such speculative technologies within mitigation scenarios creates a potential moral hazard where the promise of negative emissions tomorrow delays necessary policy action today [16]. Lackner, on the other hand, argues that the remaining carbon budgets are so small that NET deployment will be a necessary even with aggressive emission reductions, and advocates for an inclusive approach that focuses on fighting climate change using every available means [17]. With the global carbon budget quickly eroding the time for such considerations is in short supply. There is a dire need to investigate the many variables affecting the deployment of NETs in addition to developing strategies that could lead to their deployment at scale.

2.2 Negative Emission Technologies

Negative Emission Technologies such as BECCS, direct air capture (DAC), biochar as a soil amendment, enhanced weathering, afforestation and reforestation, and ocean fertilization/alkalinization, and soil carbon management [7] aid in the efforts of mitigating climate change through the removal of greenhouse gasses (GHGs) from the atmosphere [8].

Direct Air Capture (DAC)

DAC technologies are those which capture and sequester CO_2 directly from atmospheric air at ambient conditions (e.g., Klaus Lackner in 1999 [18]). The process is similar to post-combustion scrubbing technologies that remove CO_2 from flue gas only this reaction must happen at much lower concentrations [19]. The majority of DAC processes rely on employing reversible sorbents that are regenerated to capture and release CO_2. Sorbents which have a strong affinity for binding to CO_2 are typically chosen as ambient air has a very low CO_2 concentration (~400ppm) for uptake. There are a number of different sorbent-based processes being explored for DAC including aqueous hydroxide sorbents, solid alkali carbonates, and organic-inorganic hybrid sorbents [20]. This high binding affinity comes at a cost, however, as regeneration of the sorbent requires high amounts of input energy [20]. Water consumption is also a major concern for DAC deployment and is an area of further research. The perceived advantages of DAC include its ability to potentially remove CO_2 from both distributed and point sources, the flexibility of location for DAC facilities, and the potential for strategic co-location of DAC facilities with other processes to make synergistic use of multiple processes [20].

Biochar

Biochar is a highly recalcitrant carbon rich product created through the thermal decomposition of biomass under low oxygen conditions. The process for creating biochar is the identical to charcoal, however, biochar is produced for the sole purpose of application to soil as an amendment that improves productivity, carbon storage, and water filtration properties [21]. Dominic Woolf outlines a sustainable biochar concept where biomass from agricultural residues, agroforestry, and dedicated biomass undergo pyrolysis to produce bio-oil, syngas, process heat, and biochar. The bio-oil and syngas can be used to generate energy while the biochar is transported to be applied to the landscape [22]. Biochar has a number of benefits when applied to soils including improved water holding capacity, reducing nutrient loss from soils, and increasing soil carbon stocks. Biochar’s ability to enhance the productivity of agricultural and marginal lands potentially creates a positive feedback, which further enhances CO_2 removal over time. For this reason, biochar for climate mitigation is most suitable for use in regions where soil fertility is low. The mitigation potential associated with biochar application varies geographically between regions with different soil types and existing land use practices [22]. Another consideration for biochar in relation to climate mitigation is its reduction of albedo which is estimated to reduce its overall benefit for mitigation by 13 – 22% [23]. Because biochar, bioenergy, and BECCS all utilize biomass to generate negative emissions, regional studies are needed to determine the optimal approach for mitigation.

Enhanced Weathering

The chemical weathering of mineral rocks is an important process in the long-term carbon cycle that naturally removes CO_2 from the atmosphere and sequesters carbon in carbonates [24]. Enhanced weathering is a proposed geoengineering technique that involves artificially accelerating the weathering of mineral silicates and carbonates in order to bind carbon in mineral form. The process involves the mining of Olivine (Mg_2SiO_4) or calcium carbonate ($CaCO_3$). These minerals are then pulverized into a fine powder and distributed on land or in oceans where they react with surface water and atmospheric carbon dioxide to sequester carbon as bicarbonate (HCO_3^-). When enhanced weathering is applied to the ocean it also acts to increase ocean alkalinity which could effectively combat ocean acidification. Delivering negative emissions at scale through enhanced weathering would require large scale mining operations and consume significant amounts of energy associated with the mining, transportation, grinding, and distribution of the pulverized powder [24].

Afforestation

Afforestation is a land-based mitigation strategy for carbon sequestration through the establishment of new forest stands. Carbon is captured and stored through the growth of biomass and generation of forest soils. The effectiveness of afforestation as a mitigation tool is highly dependent upon geographic location of the converted land. While growing trees sequesters carbon through new plant growth, the establishment of forest stands in some regions could lower the albedo of the landscape, potentially offsetting any mitigation gained through carbon sequestration. Additionally, there are concerns that afforestation programs would compete with agricultural land which could lead to large increases in food prices [25].

Classification of NETs

All NETs involve the removal of carbon dioxide from the atmosphere to oceanic, geological or land-based sinks. Fig. 3 provides a schematic representation of carbon flows between reservoirs for a variety of NETs as well as fossil fuel and bioenergy systems for comparison.

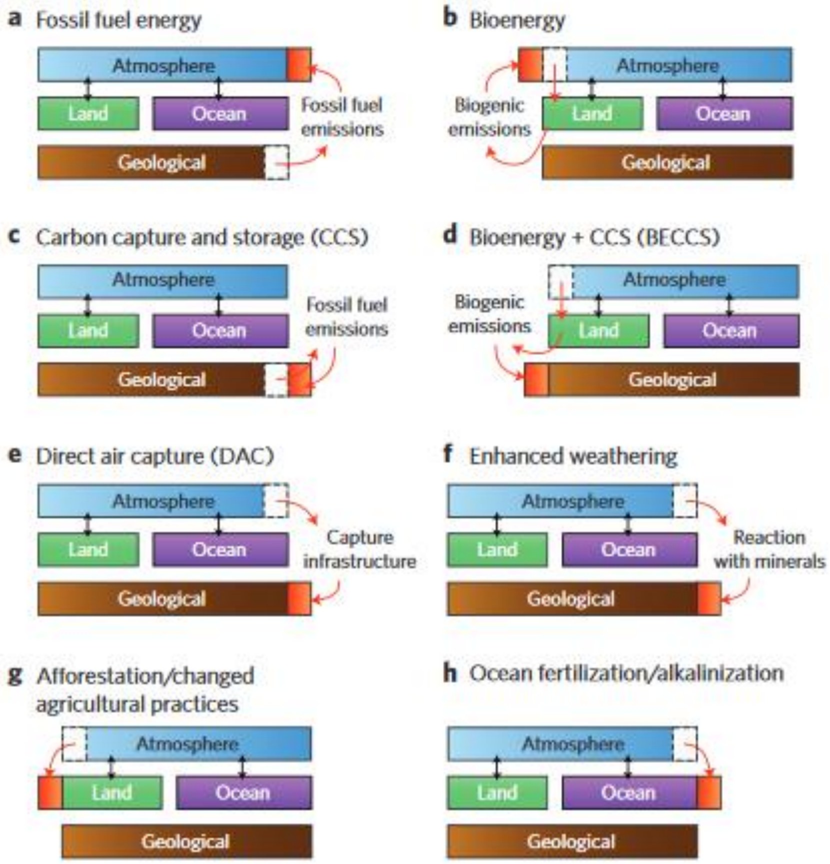


Figure 3: Schematic representation of carbon flows among atmospheric, land, ocean, and geological reservoirs for a variety of NETs.[7]

McLaren proposes a classification scheme for NETs based on the capture method and storage system, summarized in Table 1[8]. There are two categories for capture methods: direct capture, which makes use chemical reactions to extract CO_2 from the atmosphere, and indirect capture, which makes use of biological fixation of carbon via photosynthesis. There are four categories for classifying NETs by their storage system: Mineral, Pressurized, Oceanic, and Biotic. Under this classification system DAC, for example, would be considered a direct, pressurized NET whereas biochar would be considered an indirect, biotic NET.

Table 2: Classification of NETs by capture method and storage system. Based on information presented in [8]

Capture method	**Description**	**Example**
Direct capture	Capture of CO_2 by chemical scrubbing	Direct Air Capture
Indirect capture	Capture of CO_2 mediated by biological fixation via photosynthesis pathways	BECCS
Storage System		
Mineral	CO_2 is binded mineral form into rocks and soil	Enhanced weathering of mineral silicates (Olivine, etc.)
Pressurized	CO_2 is compressed into a supercritical fluid and injected into a geological storage reservoir	Carbon Capture and Storage, Enhanced Oil Recovery
Oceanic	CO_2 is captured through manipulation of oceanic chemistry	Ocean Liming, Ocean Fertilization
Biotic	CO_2 is captured in relatively stable organic sinks such as soil or recalcitrant biomass	Soil carbon sequestration, Afforestation/Reforestation

Estimated technology readiness level, deployment potential and effect on water-energy-land use nexus.

Each NET comes with its own set of technical, social, and economic constraints. Techno-economic evaluation of NETs is important as these technologies are developed. While each NET has a theoretical basis for realizing negative emissions, consideration of the scope and scale of drawdown needed to meet mitigation targets is essential. The scale of deployment of NETS will be constrained by their technical capacity, economic incentives for deployment, and their relationship with extant resources including land, water, energy, nutrients and effect on albedo. Duncan McLaren provides a global techno-economic assessment of NETs which considers the status; technical capacity and scalability; controllability; accountability, energy requirements, and cost of carbon removal [8]. These constraints are further complicated by the competition for resources from agriculture, conservation efforts, and in some cases other NETs. Biochar production and BECCS for instance, both require biomass to act as the method of capture and thus compete for the same water, land, and nutrients. The capacity, readiness, and costs of prospective NETs from this study is shown below (Fig 4).

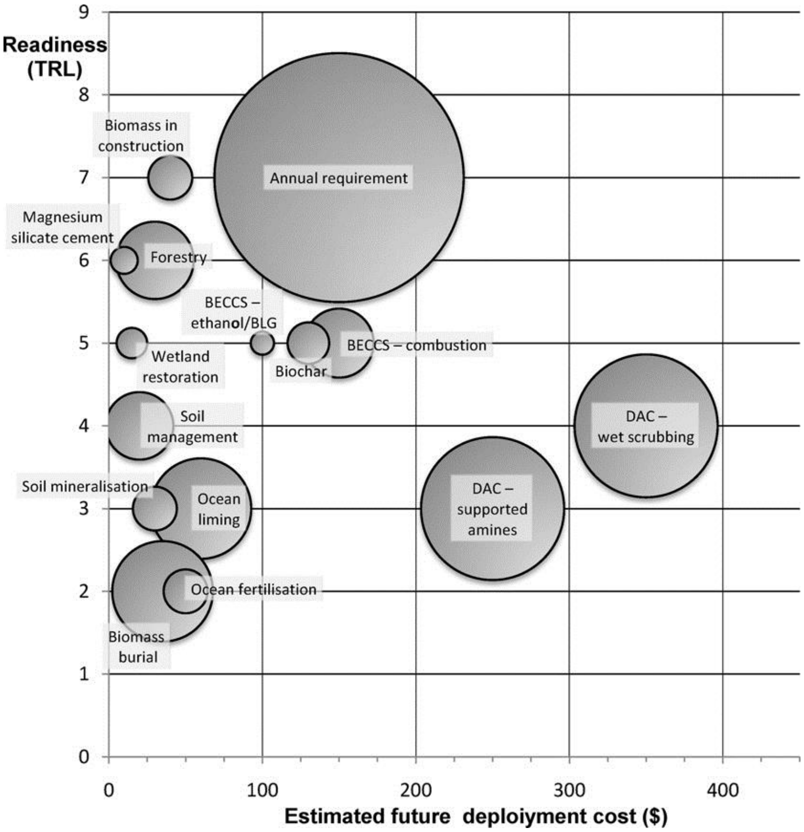


Figure 4: Potential technical capacity, technology readiness level, and future cost of deployment for a range of NETs ($/ton-CO2 removed)Bubble sizes are proportional to potential technical capacity, this study assumed an annual requirement of 24GtCO$_2$ per year [8].

NETs that are primarily considered in IAMs are not currently ready for commercial deployment. Those that are, do not offer substantial negative emissions at the scale needed for meeting mitigation targets. Given the scale of deployment and the urgency of action needed, there is a need to develop commercialization strategies for the most promising NETs. Placing each NET within the climate-land-energy-water nexus will be important for making decisions about the structuring of policy frameworks needed to support their development.

Pete Smith has published two papers, [7] and [26], that provide an estimation of the global resource impacts associated with the deployment of several prominent NETs consistent with mitigation targets predicted for 2100. The first paper, focusing on BECCS, DAC, enhanced weathering, and afforestation/reforestation to estimate the land requirements, energy requirements, water requirements, nutrient impacts and changes in albedo associated with each assumed negative emission potential. The negative emission potential of DAC and BECCS were assumed to be equal to 3.3 GtCeq yr^{-1}, the median scale of deployment found in IAMs consistent with < $2^{o}C$ mitigation targets [7]. For enhanced weathering and afforestation/reforestation the negative emission potential was taken from literature values and ranges were determined to be 0.2 – 1GtCeq yr^{-1} and 1.1 – 3.3GtCeq yr^{-1} respectively [7]. The second study followed a similar method but focused on soil carbon sequestration and biochar at a deployment range of 0.7 – 1.3GtCeq yr^{-1} [26]. Global impacts for land requirements, energy, water use, and costs from these analyses are shown in Fig 5.

Each NET has its own advantages and disadvantages. The two NETs expected to deliver the greatest negative emissions require substantial resources for mitigation. A global BECCS deployment of 3.3GtCeq yr^{-1} was found to require 720 km^3 yr^{-1} of water, between 380-700 Mha of land, and would produce nearly 170 EJ of energy [7]. DAC was found to be less intensive in terms of water (10 – 300 km^3 yr^{-1}) and land (nearly zero), but requires a substantial amount of energy (156 EJ yr^{-1}) for deployment [7]. It’s worth noting that the energy requirement of DAC units to operate make it somewhat difficult to accurately place within the energy-carbon-water nexus. The source of energy used to run the units would pose different resource implications for deployment at scale. For instance, if solar electricity is used the land requirement would necessarily increase while the high water use associated with thermal power generation could increase the water footprint. Strategic colocation of DAC with other energy generation facilities and CCS sites is an active field of research aimed at improving the viability of the technology as a strategy for climate mitigation and carbon removal [27].

Afforestation and reforestation were found to offer a range of resource impacts depending on their level of deployment. The range of land and water impacts were 320-970 Mha and 370-1040 km^3 yr^{-1} respectively, with relatively low costs associated relative to other NETs[7]. Enhanced weathering was found to have a low land (2 – 10 Mha) and water requirements (0.3 – 1.5 km^3 yr^{-1}), but requires 46 EJ yr^{-1} of energy associated with the mining, crushing, transportation, and dispersion of mineral. This activity incurs some steep logistical costs and the lack of policy frameworks for carbon storage make it relatively cost prohibitive.

Soil carbon sequestration and biochar, were found to offer the most sustainable use of resources, however their potential for delivering negative emissions at the gigatonne scale are more limited. Both improve the water holding capacity of the soil and aid in nutrient retention making them attractive options for incorporation into existing agriculture and forestry systems. The potential for improving soil fertility suggests that biochar deployment offers the greatest mitigation benefits when applied to regions with poor soils [22]. Soil carbon sequestration requires little additional energy while biochar production produces energy at a range of 20-50 GJ tC^{-1} depending on the feedstock and conversion process used [26].

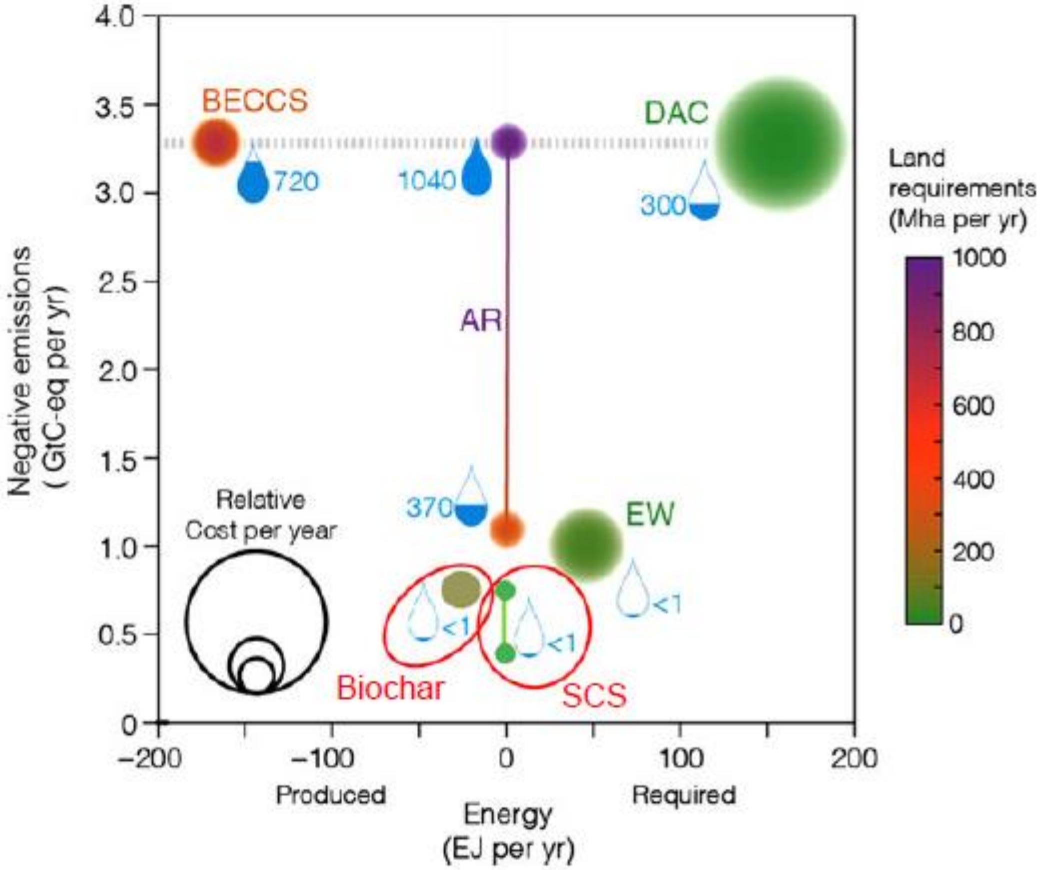


Figure 5: Comparison of the global resource impacts of soil carbon sequestration (SCS), biochar, enhanced weathering (EW), Afforestation/Reforestation (AR), BECCS, and DAC. Water requirements shown as droplets in units of km3 yr-1 [26].

Determining the resource implications for NET deployment becomes especially important when moving from the global level to the regional level. Geographic differences in climate, vegetation, water availability, arable land, and proximity to urban centers impact the suitability of NETs for a given region. Careful accounting of water, emissions, land, and energy footprints associated with the deployment of NETs within a regional context should provide the basis for informing policy frameworks for mitigation.

Pairing appropriate NETs with suitable locations and resources could reduce the potential for negative impacts. Moreover, some NETs can be paired synergistically to support the development of others. This kind of mutual synergism is not difficult to imagine as increased yields from land application of biochar could bolster the available biomass for BECCS or further production of biochar.

2.3 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS describes a suite of mitigation technologies that combine the use biomass for energy with geological carbon capture and storage. CO_2 in the atmosphere is fixated by photosynthesis in the growth of new biomass which is subsequently harvested and transported for bioenergy application. The energy derived from biomass can be deployed for a range of uses depending on the conversion pathway pursued. Biogenic CO_2 is captured at the bioenergy plant either before combustion, during conversion of biomass to fuels or after combustion in the flue gas in the case of a thermal plant. The captured CO_2 is then compressed and transported for storage typically in deep saline aquafers or depleted oil fields for enhanced oil recovery. A general process description for BECCCS is shown in Fig 6.

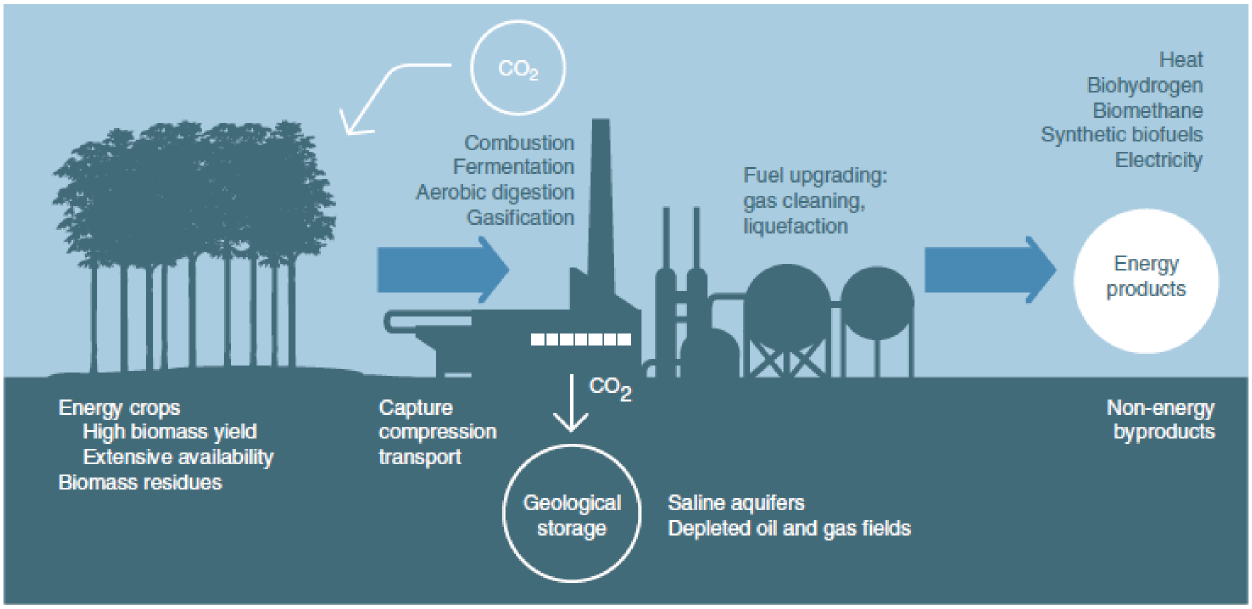


Figure 6: General process description for BECCS systems [28].

The ability for BECCS systems to effectively function as a NET is dependent on a variety of factors in the life-cycle of the system including direct and indirect land-use changes as a result of bioenergy production, GHG emissions from fertilizer inputs, transportation, and harvesting, carbon capture rate, and long-term changes in carbon stocks within the landscape. Detailed greenhouse gas accounting of the entire system is necessary to ensure that BECCS deployment can result in net negative emissions.

BECCS Development Pathways

Conversion Routes for Bioenergy

Another major barrier to the deployment of BECCS is the commercial scalability of the technology, which underscores the need to rapidly develop commercialization strategies that can actualize pathways to achieve net-negative emissions. There are a range of biomass to energy conversion pathways that could potentially be utilized with CCS technology to generate negative emissions. There are three different categories for describing conversion routes for biomass to energy: thermochemical, biochemical, and mechanical. Thermochemical conversion includes combustion, pyrolysis and gasification of biomass. Biochemical conversion involves the use of organisms to convert the chemical energy within the feedstock to fuels or chemicals some examples include fermentation for producing ethanol, and anaerobic digestion to produce methane for fuel. Mechanical conversion involves the compression and extraction of oil from oilseed crops which can undergo further esterification to produce biodiesel. Each conversion pathway for bioenergy provides unique opportunities and challenges for integration with carbon capture technology and suitability of feedstock.

De-carbonization of the transportation sector has proven to be a difficult challenge. The distributed nature of transportation emissions makes them more difficult to mitigate through carbon capture technology. BECCS pathways could produce decarbonized or carbon-negative fuels if the conversion process incorporates carbon capture and storage. Production pathways for liquid biofuels are shown in Fig 7. Bio-methane from anaerobic digestion, and Fischer-Tropsch synthesis with CCS are two notable biofuel production pathways that could potentially function as NETs.

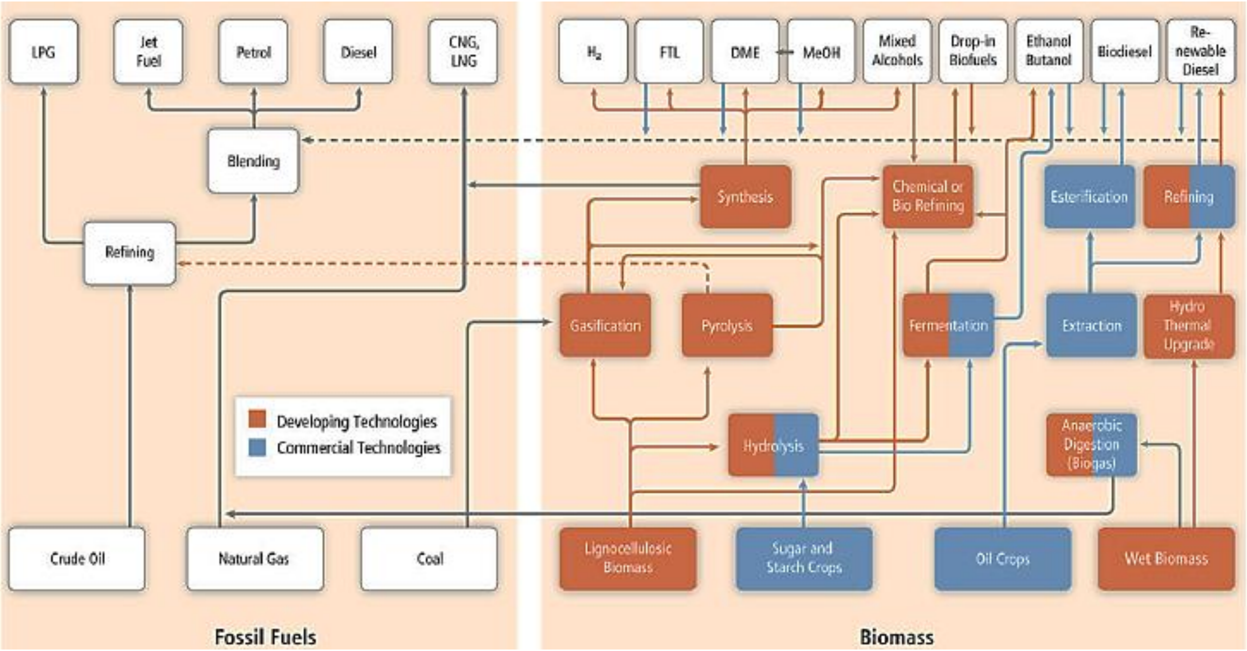


Figure 7: Production pathways for liquid fuels from biomass and fossil sources [29].

Carbon Capture and Storage

CCS is one, if not the most critical technologies for mitigating future greenhouse emissions, yet it is still vastly underdeveloped at the commercial level. Whether applied to biomass to generate negative emissions, or used in fossil-based energy infrastructure to reduce the emission profiles of our energy system, CCS technology will need to be up-scaled dramatically in order to meet mitigation targets. Leung et al. have reviewed the current status of state of the art CCS technologies and provide an overview of various aspects including CO_2 capture, separation, transport, storage, leakage, monitoring and life cycle analysis [30].

Post-combustion CCS systems are currently the most technically developed and are expected to be the first generation of (BE)CCS systems deployed as existing coal fire power plants can be retrofitted for post-combustion CCS and bioenergy. However, post-combustion systems have several drawbacks such as high regeneration enthalpy, thermal and oxidative degradation of amine-based solvents, and low carbon dioxide partial pressure constraint [31]. Pre-combustion carbon capture systems adapt long established chemical processes for production of hydrogen and chemical commodities toward the capture of CO_2 in gasification based energy systems [32]. Advantages of pre-combustion CCS include higher sorption efficiencies, as the water-gas shift reaction produces a high pressure stream of CO_2 and H_2, resulting in lower energy demand for CO_2 separation and compression compared to post-combustion CCS [30]. This advantage however is potentially offset by high parasitic energy requirements for regenerating the absorption solvent, and limited experience due to the relatively small number of gasification based plants operating commercially.

Gasification of coal or biomass creates a stream of CO, H_2, and small quantities other trace gases, called syngas. Following gasification this syngas is passed through a water-gas shift reactor where the CO reacts with steam to form CO_2 and H_2 under high pressure conditions. This "dirty" syngas is then passed through an acid gas reactor to remove H_2S and a high pressure stream of purified CO_2 from the syngas mixture. This CO_2 is then further compressed to supercritical state and can then transported for injection into geological reservoirs.

Commercialization Strategies

Daniel Sanchez proposes a strategy for commercial deployment of BECCS through two thermochemical conversion pathways via gasification that co-utilize biomass and coal: Integrated Gasification Combined Cycle with CCS (IGCC-CCS) and Fischer-Tropsch synthesis with CCS (FT-CCS) [33]. These gasification-based routes for BECCS utilize pre-combustion CCS technology discussed previously to capture these emissions. For developing the commercialization strategy, Sanchez focuses on how co-utilization of coal and biomass provide flexibility as attractive attribute for investment at commercial scale. Dedicated biomass facilities face several challenges that can be overcome by co-utilization of coal such as higher efficiency, lower feedstock variability, and lower biomass required per unit of energy produced [33]. A wide range of biomass/coal co-utilization ratios could potentially be used to produce low-carbon, carbon neutral, or carbon negative fuels and electricity. As such, the costs associated with bioenergy production and CCS can be balanced as markets, policy frameworks, and biomass availability change. Additionally, rapid upscaling of CCS necessitates the commercial scale development of pipelines and infrastructure for geological injection of captured CO_2; an effort that is enhanced by the economies of scale associated with coal.

Fischer-Tropsch synthesis is a process where syngas from gasified biomass or coal is reacted with a catalyst to generate liquid FT fuels that can be further refined into a range of hydrocarbons, including petroleum replacements such as diesel and gasoline. Fischer-tropsch generation can be combined with a combined cycle system for polygeneration of both fuels and electricity [34]. When the FT process incorporates CCS technology the greenhouse gas emissions can be significantly reduced. If sustainably sourced biomass is utilized instead of coal the FTL fuels could become negative in its overall net GHG emissions [34]. The net impacts of FT-CCS vary with choice of biomass feedstock, management decisions, direct and indirect land use changes as a result of bioenergy deployment, transportation logistics, portion of coal and biomass in feed, and distance from CO_2 injection site.

Colocation of Biomass and CO_2 Storage Sites in the U.S.

Another major point of consideration for BECCS is the location of plant. The USGS estimated that the total CO_2 storage capacity of suitable geological formations in the U.S. is approximately 3000 $GtCO_2$, however this storage capacity is limited to specific regions where suitable storage basins exist, with the coastal plains basin accounting for 1900 $GtCO_2$ (~65%) of the total capacity [35]. As such, the viability of BECCS varies regionally as the potential for deployment is influenced by the presence of both abundant sources of biomass and suitable storage basins for CO_2 injection, particularly in the near term where long distance CO_2 and biomass transport remains limited [36]. A recent paper by Baik et al investigated the colocation of biomass resources with geological storage basins for CO_2 by leveraging county level biomass availability data from the billion-ton report [37] and the USGS National Assessment of Geologic Carbon Dioxide Storage Resources [38]. The results of their analysis indicates that approximately 30% of the biomass potentially available for BECCS in 2020 is collocated with suitable CO2 storage sites, with the near term potential for BECCS deployment reduced from 370 MtCO2/year to 100 MtCO2/year using the base case scenario from BT16. Fig 8 below shows county level BECCS technical potential for 2020 reported in Baik et al.

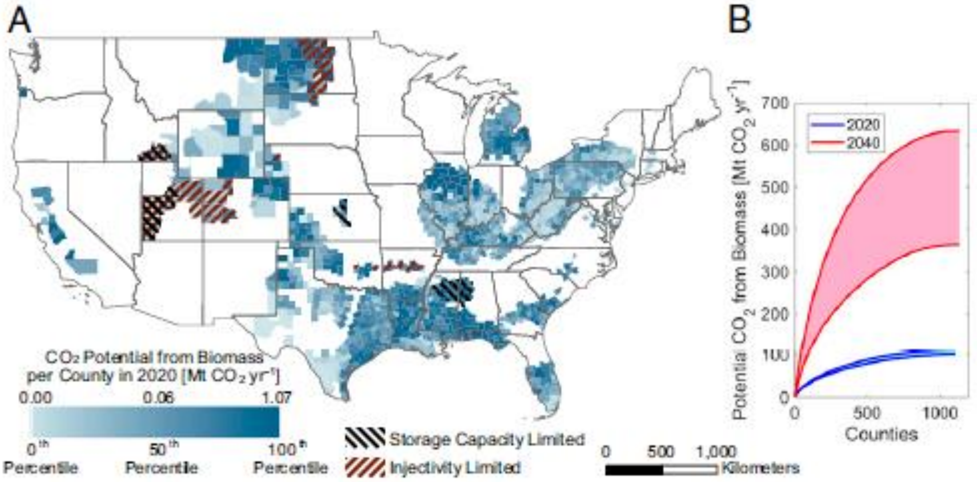


Figure 8 Distribution of technical potential of BECCS (A) Map of technical potential of CO_2 that would be available from biomass in 2020, under the BT16 base case scenario. Regions with highest CO_2 potential and co-located storage sites are northern Illinois basin, the Gulf region, and western North Dakota. (B) Cumulative sum of the potential CO_2 in counties with suitable storage sites for 2020 and 2040 [36].

The Southeast region of the U.S. has both adequate capacities for CO_2 storage in its geological reservoirs and significant volumes of biomass potentially available for BECCS application, making it a potential candidate for near-term deployment.

2.4 Biomass Feedstock – Loblolly Pine in the Southeast

The Southeastern United States has vibrant industry for forestry products with long established markets for the timber and pulp and paper industry. In Georgia, for instance, over 60% of the land base is comprised of forested land scape (Fig. 9) [39]. This large pool of resources has led to a growing interest in utilizing excess forestry residues for bioenergy production. In recent years, the production of wood pellets for bioenergy in the region has grown substantially. This growth in wood utilization for bioenergy has been largely driven by the EU's 20-20-20 policy which includes 20% increase in energy efficiency, 20% reduction in CO_2 emissions and 20% renewable energy by the year 2020 [40].

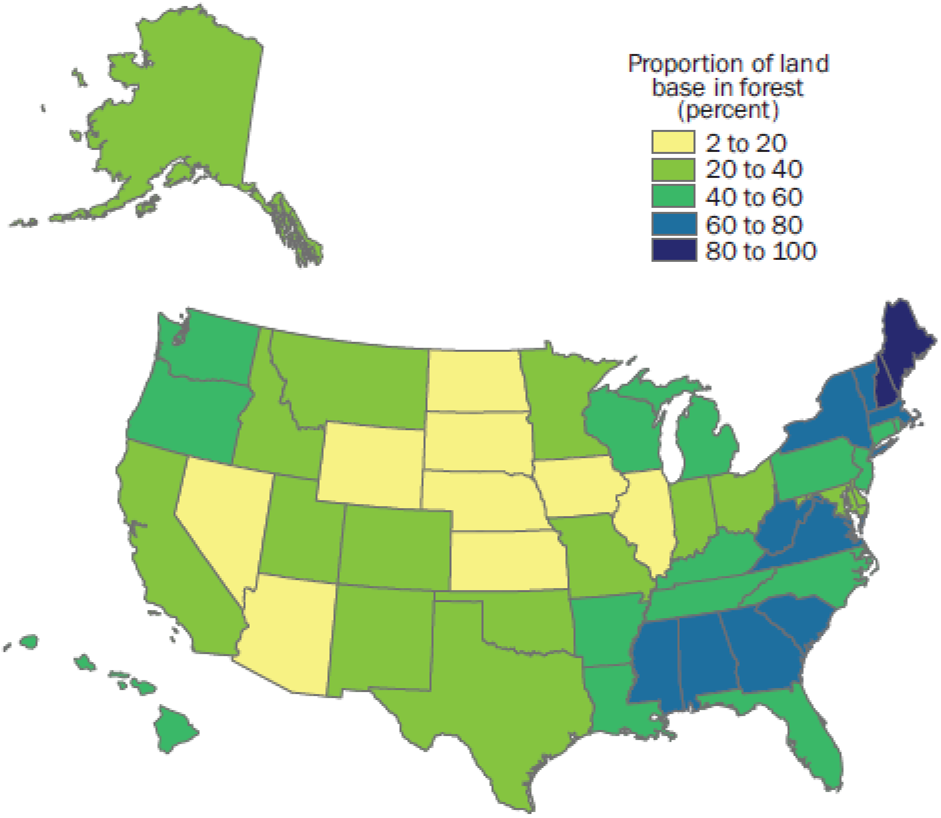


Figure 9: Percent of total land that is forested, by State. [39]

Much of the energy available for bioenergy application from forestry products comes from logging residues, sawdust from timber mills, and tree thinning for timber harvest improvement. Demand from European nations, The UK in particular, has led to the rapid growth of the wood pellet industry. Georgia's foresters have taken advantage of these developments and has become one of the major contributors to wood pellet production in the United States. In fact, Georgia is home to the worlds single largest wood pellet producer – Georgia Biomass, LLC. [41]

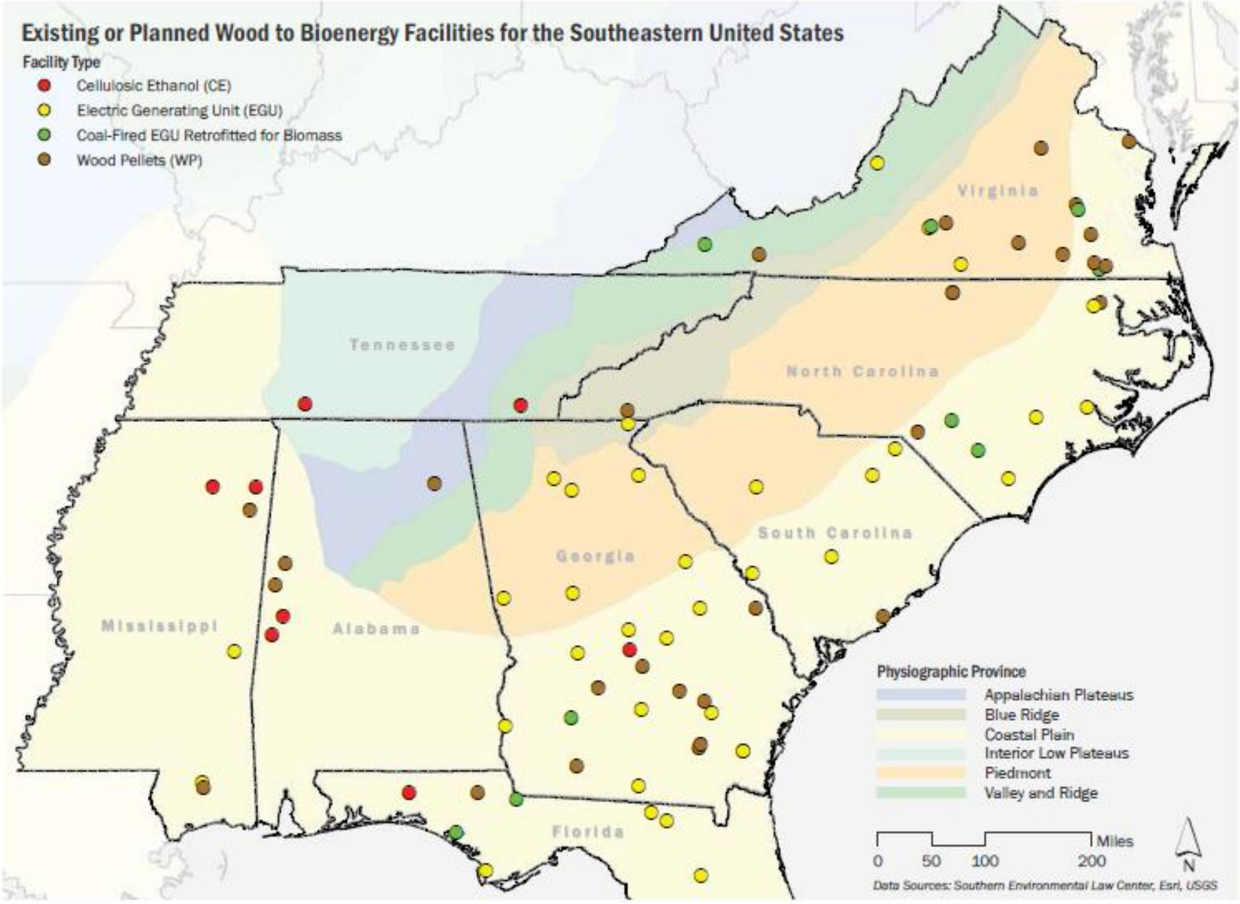


Figure 10: Biomass Energy facilities in the Southeastern United States [41]

Carbon accounting and sustainability assessment of forestry feedstock's is a complicated process due to the spatial and temporal variability, commercial species, and local geographic differences that influence carbon dynamics given within plantation systems. Wood use for bioenergy systems that burn wood pellets have been found to offer significant greenhouse gas reductions over their lifecycle when compared with fossil utilities [42]. However, these carbon reductions are highly dependent on the source of feedstock, energy associated with the biomass supply chain, the conversion pathway for energy production, and the validity of carbon neutrality on a case by case basis. Hanssen found that bioenergy from existing southeastern softwood plantations reduces greenhouse gas emissions compared to EU fossil grid technology, and even offered reductions over pulp and paper production if the same feedstock is instead used for bioenergy [43].

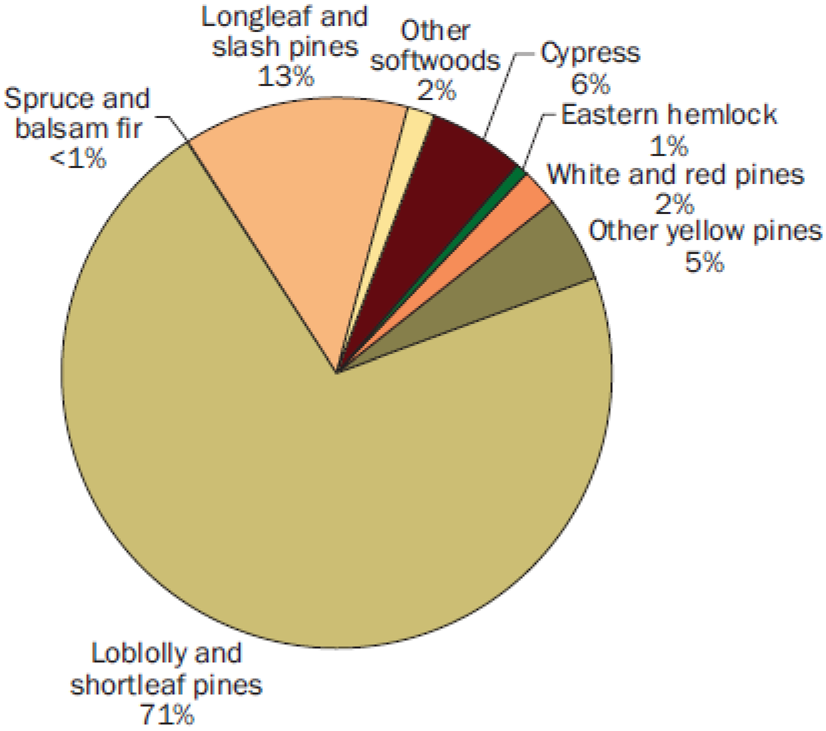
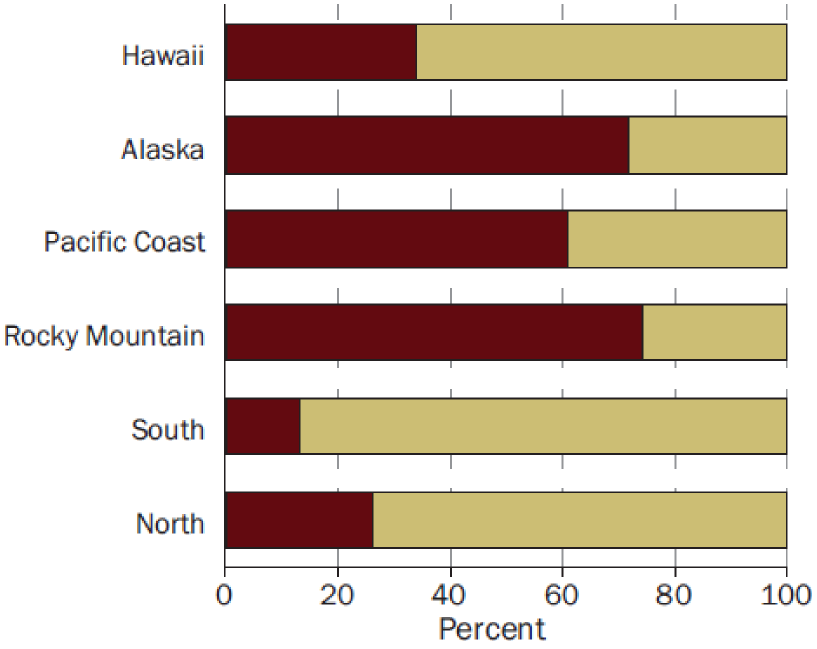


Figure 11: Proportion of softwood growing stock species by group in the South, 2012 [39]

Loblolly pine plantations in the southeast are a major contributor to the total forested acreage within southeastern United States [39]. In fact, loblolly and shortleaf pine species account for the greatest proportion of softwood species represented in the south (Fig 11). Longitudinal studies of loblolly pine over multiple rotations in the southeast have demonstrated that under best management practices silvilculture cultivation of loblolly pine retain their nutrient stocks [44]. Gresham found that nitrogen and phosphorus pools in the second rotation of loblolly pine in the soil, vegetation, and needles were either equal to or greater than the pools in older generations [44].

The majority of forested land in the southeast region is dominated by private land ownership for plantation silviculture (Fig. 12) [39]. Private ownership of forested land has likely contributed to an increase in total acreage within the southeast as timberland remains a profitable investment due to large markets for forestry products. That much of the forested land in the region is already being utilized for wood production for harvesting in pulp and paper as well as timber suggests that the use of forestry products from plantations is more suitable for bioenergy applications that wood that would be harvested from natural forests [43].



	North	South	Rocky Mountain	Pacific Coast	Alaska	Hawaii
			million acres			
🟥 Public	46.5	32.7	97.5	51.4	92.5	0.6
🟨 Private	129.1	212.0	33.8	32.9	36.1	1.2

Figure 12: Proportion of public and private ownership of forested land in the United States [39]

CHAPTER 3

Methods

3.1 System Boundaries and Data Sources

First, a whole system overview is presented which establishes system boundaries and summarizes sources of data followed by an in depth description of the methods and assumptions used for developing each component of the model. Fig. 13 presents a conceptual, whole system overview of a hypothetical Fischer-Tropsch plant. Forestry residues, thinnings and a portion of pulpwood from loblolly pine are used as the biomass feedstock input for various harvesting scenarios. Forest Vegetation Simulator (FVS) was used to develop a suitable growth and yield model for a southern loblolly pine plantation [45]. The assumed federate for this analysis is 1000 tonnes/d for 365 days per year. A range of woodshed sizes was determined for eight harvest scenarios further described in the following section. Table 3 lists the primary sources of data used for developing each component of the model. Carbon balances at the plant level are derived from the CBTL-RC-CCS and BTL-RC-CCS simulations presented by Liu et al. [34], for co-utilization and dedicated biomass scenarios respectively.

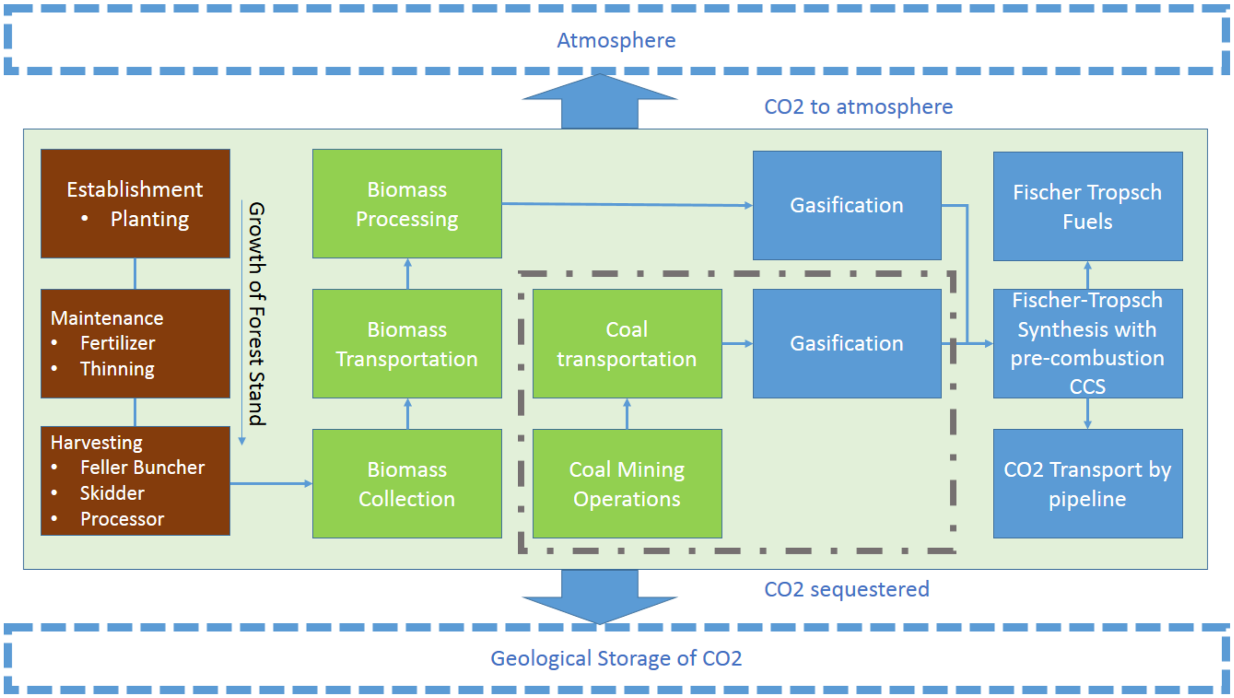


Figure 13: Conceptual overview of the system boundary considered for estimating the greenhouse gas, land, energy, and water implications of producing fuels from FT synthesis with CCS. Grey dashed line indicates processes considered in co-utilization configurations.

Table 3: Summary of primary data sources used to develop each component of the model.

System Component	**Source of data**
Growth and Yield model	FVS – Southern Variant [46]
Establishment	
Seed orchard and Nursery	[47]
Site preparation – chopping, piling, burning, disking, bedding, herbicides, and planting	[48]
Maintenance	
Fertilizer – 200 lb. of Nitrogen applied in year 4	Calculated,
Thinning	[47]
Harvesting	
Felling, bunching, skidding, de-limbing, loading, chipping	[48]
Transportation	Calculated based on [49]
Fischer-Tropsch Plant level	[34]
Water Model	[50-54]

3.2 Forest Growth Model

The growth and yield of loblolly was modeled with the USDA's department of forest service's southern variant of the Forest Vegetation Simulator (FVS) [46]. FVS is a distance-independent, individual tree forest growth model used for management and analysis objectives. FVS comes with a variety of extensions and post-processors that can be used to quantify forest dynamics over time for a variety of different forest systems based on user-generated inputs.

The Southern variant for FVS was covers all states within the southeastern region of the United States and is suitable for developing growth and yield projections for loblolly pine grown in the region. The variant was originally developed in 1996 using relationships found in the Southeast TWIGS model applied to Alabama, Georgia and South Carolina, but has been further developed using FIA data from all 13 states within the Southern Region (Fig. 14) [46].

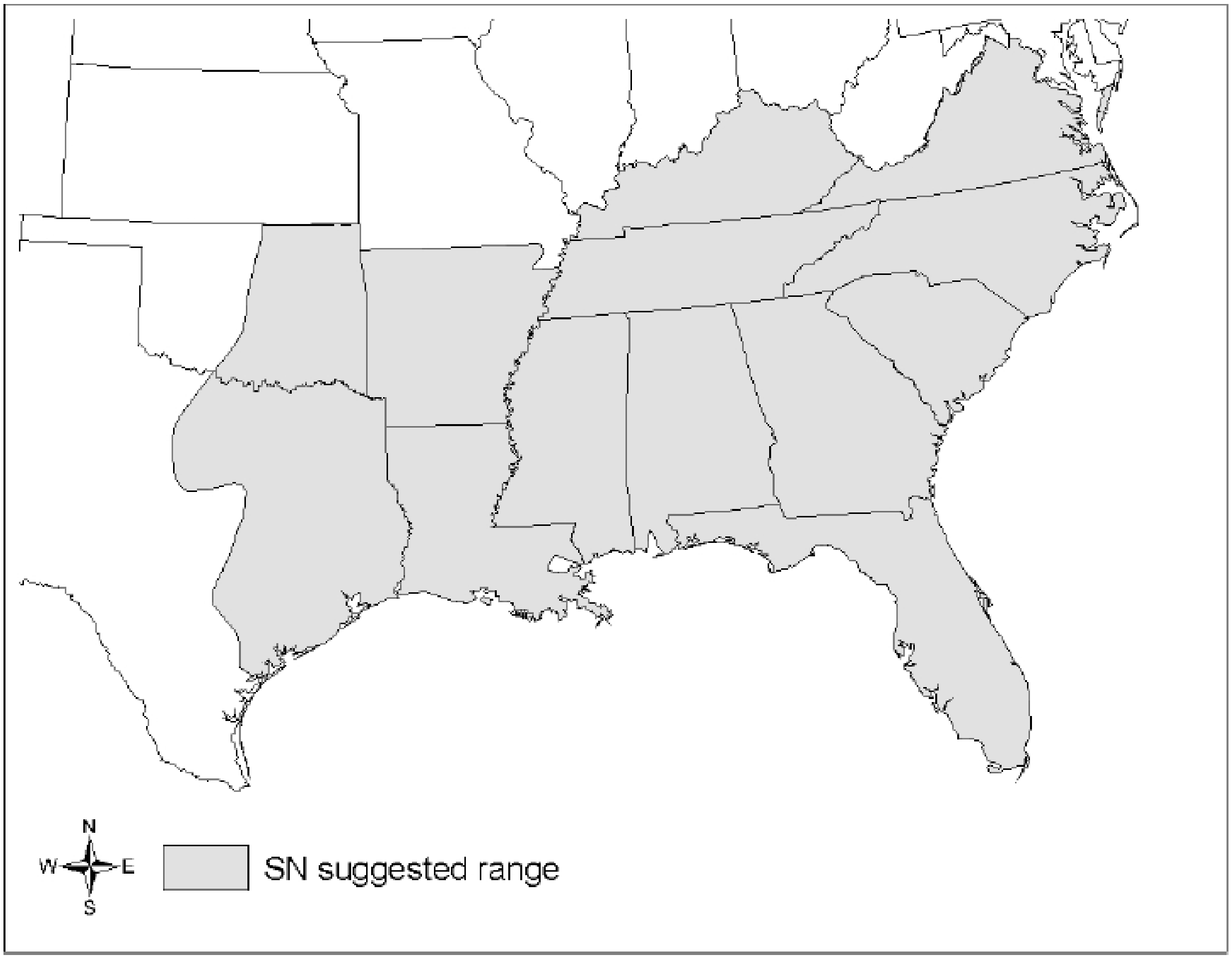


Figure 14: Geographic range covered by the Southern Variant of FVS.

For this study, the growth and yield model begins with a bare ground stand (i.e. no biomass at year 0). The stand is planted in 2018 with loblolly pine at a density of 600 trees per acre, uniformly distributed. The time horizon for the FVS growth and yield model is limited to 40 cycles for a given time interval. The time interval for the growth and yield models were set to 1 year, leaving a 40-year time horizon for the FVS simulation. A variety of management activities for silvicultural operations were simulated inside FVS. Fertilizer in the form of ammonia is applied at a rate of 200 lbs of N/acre in year 4. Thinning operations were considered primarily to reduce susceptibility to pine beetle attacks, which increases as the basal area and stand age increase. The thinning from below option in FVS simulates the removal of the smallest diameter trees first until the residual basal area meets the input conditions. Thinning from below was scheduled to occur whenever the basal area of the stand surpassed 130 ft^2/acre to a residual basal area of 70 ft^2/acre. Standing dead trees are also cut each time a thinning occurs, adding downed woody debris to the surface fuel load. FVS simulation parameters are summarized below in Table 4.

Table 4: Summary of parameters used to develop FVS growth and yield model.

Parameter	**Value**	**Unit**
Bare ground initialization	0	Trees per acre
Initial Planting Date	2018	Year
Planting density	600	Trees per acre
Time Horizon	40	years
Fertilization	200	Lb./acre in year 4
Thin from below when basal area exceeds	130	ft^2/acre
Residual basal area (post thinning)	70	ft^2/acre

The Fire and Fuels Extension (FFE) allows for tracking the mass of biomass in dead trees, limbs, shrubs and litter, with option for creating compute variables to track wood across a range of debris sizes. To estimate recoverable forest residues available for bioenergy use, a variable for bioenergy residue was created using the compute surface fuel loading function to quantify recoverable debris. Debris class range for this recoverable bioenergy residue variable was set between three and twenty inches. Bioenergy residues are assumed to be recoverable at the time of harvest (not thinning).

A set of harvesting schedules were programed using Excel for eight scenarios of biomass utilization representing the intensity of biomass harvest and the rotation age of the plantation at harvest. All scenarios include forest residues and thinnings, but high intensity and low intensity scenarios differ based on the allocation of pulpwood for energy use. Low intensity bioenergy harvest scenarios allocate 30% of the wood present in the pulpwood category to bioenergy feedstock, while high intensity bioenergy harvest scenarios allocate 70% of the wood present in the pulpwood category to bioenergy feedstock. Available wood per acre was estimated on an annualized basis for each scenario by summing the total yield for bioenergy feedstock and wood products at final harvest and dividing by the age of the plantation at harvest. The required size of the woodshed was estimated by dividing the assumed feedstock rate of 1000 dry tonnes/d by the annual availability of biomass feedstock on a per acre basis. Table 5 provides a description of each harvesting scenario along with percentage of total yield appropriated for bioenergy harvest in each scenario.

Table 5: Summary of harvesting scenarios for estimating required woodshed area. Description is years to harvest and low (30% of pulpwood) or high (70% of pulpwood) intensity bioenergy harvest.

Scenario Name	*Description*	*Percentage of total yield allocated for bioenergy*
SL20	20y, low	34%
SL25	25y, low	29%
SL30	30y, low	25%
SL35	35y, low	19%
SH20	20y, high	72%
SH35	25y, high	63%
SH30	30y, high	51%
SH35	35y, high	47%

3.3 Emissions from Silvicultural Operations

Data (usually on an area basis) for the silvicultural operations come from a variety of sources. The seed orchard, nursery, and thinning lifecycle emissions come directly from an LCA of loblolly pine plantations [47], while the emissions associated with the site preparation of loblolly pine plantations are assumed to be equivalent to similar slash pine plantations in the U.S

South [48]. The fertilization management option for FVS allows for the simulation of 200 lbs of N/acre as a fertilizer treatment. Emissions from the use of fertilizer occur both through the production of fertilizer at the plant level and from the evolution of nitrogen as nitrous oxide emissions from microbial denitrification. In the case of fertilizer production, Wood and Cowie determined that the process for ammonia production involves the release of 1495.5 gCO2eq/kgN produced [55]. Emissions from nitrous oxide evolution were calculated using a default emission factor based on the following equation:

$$GHG_{N_2O} = C_N * EF_{N-N_2O} * \frac{44}{28} * GWP_{N_2O} \qquad (1)$$

Where GHG_{N20} is the greenhouse gas emission of evolved nitrous oxide ($kgCO_2eq/ha$), C_N is the application intensity of ammonia (kgN/ha), EF_{N-N2O} is the portion of nitrogen evolved as nitrous oxide, 44/28 is the molecular weight ratio of N_2O to N_2O as N, and GWP_{N2O} is the global warming potential of nitrous oxide over 100 years. For N_2O emissions after land application, the IPCC default emission factor (EF_{N-N2O}) of 1.25% of applied nitrogen is emitted as N_2O, and the 100-year global warming potential of N_2O is 298 gCO_2eq/gN_2O [2]. Emissions from N_2O were determined to be 1312.2 $kgCO_2/ha$. Thus, the total greenhouse gas emissions for fertilizer application was found to be 1646.54 $kgCO_2eq/ha$. Global warming impacts from silvicultural operations associated with the establishment, maintenance and harvesting of the loblolly pine plantation stand are summarized in Table 6.

Table 6: Global Warming Impact of Silvicultural Operations.

	Global Warming Impact (kgCO2eq/ha)	**Source**
Seed Orchard	**34.43**	[47]
Nursery	**4.35**	[47]
Site preparation	**946.00**	[48]
Chopping	91.00	
Piling	484.00	
Burning	67.00	
Disking	121.00	
Bedding	121.00	
Herbicides	62.00	
Planting	**181.00**	[48]
Fertilization	**1,646.54**	Calculated
Nitrogen application	1,312.20	
Embodied Emission from production	334.35	[55]
Thinning	**982.23**	[47]
Felling	355.39	
Skidding	314.85	
Loading	311.99	
Harvesting	**1,617.00**	[48]
Felling and bunching	227.00	
Skidding	302.00	
Delimbing	302.00	
Loading	302.00	
Chipper	484.00	
Total	**5,411.55**	

Using this LCA data for the establishment, maintenance and harvest of forestry residues, the global warming impact of silvicultural activities was calculated for each harvest scenario on a dry mass basis by dividing the land based emission factor by the total yield of both wood products and bioenergy residues after one rotation of growth and harvest. For harvest scenarios with 20 and 25-year rotation ages there is one instance of thinning. For harvest scenarios with 30 and 35-year rotation ages there are two instances of thinning and the associated emissions are counted twice.

From the forest stand, harvested biomass is transported to the Fischer-Tropsch plant, assumed 50 miles one way. Zhang et al. have conducted detailed life-cycle assessment of forest biomass harvest and transport for bioenergy in Michigan [49]. In order to calculate emissions from transportation, their analysis assumes a 41 tonne load capacity with 50% loaded miles, a ten-year lifetime of use with 750,000 total miles [49]. Using their total GHG emission factor of 0.117 kg CO_2eq/tonne-km delivered, emissions from transportation of forest biomass are 9.4 kgCO_2/tonne delivered at the plant gate.

3.4 Plant Model

Carbon simulation for gasification based Fischer-Tropsch synthesis with CCS at the plant level was developed based on the plant and process configurations for dedicated biomass-to-liquid (BTL) and coal and biomass-to-liquid (CBTL), using the recycled (RC) syngas scenarios found in Liu et al. [34]. The RC process configuration for the CBTL scenario (Fig. 15), maximizes production of liquid fuels by recycling unconverted syngas, as opposed to a once through configuration that utilizes unconverted syngas for additional electricity generation and export via gas turbine combined cycle. In the RC design, unconverted syngas is recycled back through the synthesis reactor by way of an autothermal reformer that provides a mixture of CO, H_2, and CO_2 upstream of the acid gas removal unit. This recycle loop features a purge stream that prevents the buildup of inert gasses. These gases are collected and mixed with light gasses from the refining island and sent to the power island to provide fuel for a steam Rankine cycle, which generates electricity. This electricity runs the facility including CO_2 compression, pre-processing, and drying of feedstock, plus a small amount of additional electricity for grid export

[34]. Lui reports electricity export as a ratio of electric output/feedstock input (HHV basis) of 0.5 and 0.4 for BTL-RC-CCS and CBTL-RC-CCS respectively. These factors were used to estimate excess electricity based on the input feedstock.

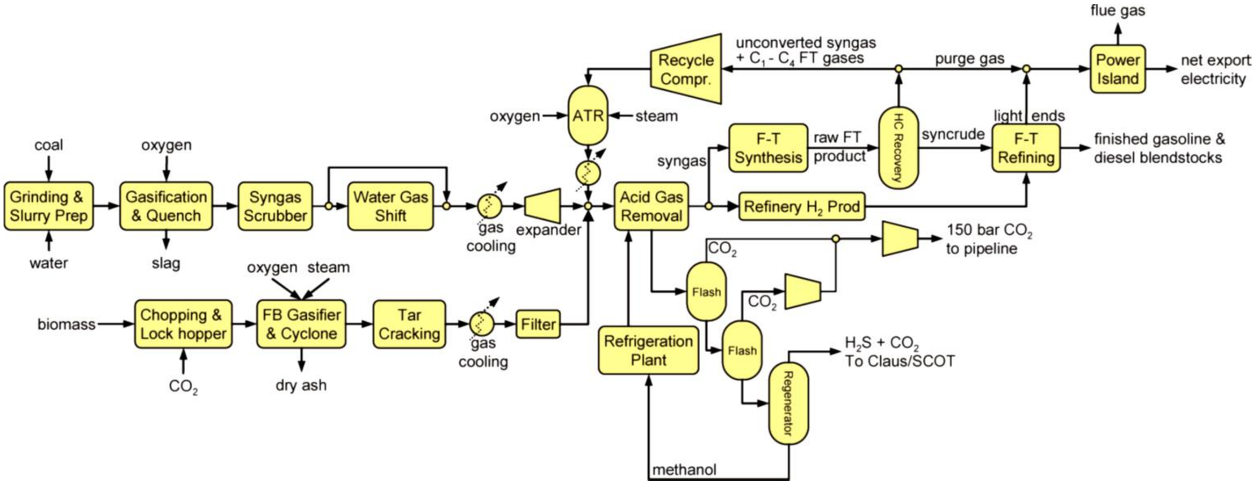


Figure 15: Process configuration for CBTL-RC-CCS for maximum fuel production [34]

The plant level carbon simulation is used to allocate input feedstock carbon to various compartments, including compressed CO_2 for capture and storage and char which result in sequestration, and carbon in finished FT fuels and vented to the atmosphere. The finished fuel mix of the FT liquids consist of 63% diesel and 37% gasoline. Diesel is assumed to have an average molecular structure of $C_{12}H_{24}$, a density of 0.83 tonnes/m^3, and a specific energy of 35.8 GJ/m^3. Gasoline is assumed to have an average chemical structure of C_8H_{18}, a density of 0.75 t/m^3, and a specific energy of 34.2 GJ/m^3. Production capacity of FTL fuels for diesel and gasoline for each scenario was estimated based on the following equations:

$$V_D = \frac{f_D * m_C * \frac{MW_{C_{12}H_{24}}}{MW_{C_{12}}}}{\rho_D}$$

$$V_G = \frac{f_G * m_C * \frac{MW_{C_8H_{18}}}{MW_{C_8}}}{\rho_G}$$

Where the subscripts D and G refer to diesel and gasoline respectively, V is the volume (m^3) of fuel product produced, m_c is the total mass of carbon input per day and MW_{CxHx} refers to the average molecular weight of the given hydrocarbon compound and MW_{Cx} refers to the molecular weight of elemental carbon in the fuel, and ρ is the density of the given fuel. Energy content (E) was determined by multiplying the volume (V) of fuel produced by the specific energy (U) of each respective fuel.

$$E_D = V_D * U_D$$

$$E_G = V_G * U_G$$

3.5 Carbon Accounting Framework

Carbon neutrality and carbon payback time

The carbon released from the combustion of biomass has long been considered carbon neutral in a variety of accounting schemes that track GHG emissions of bioenergy systems [56]. The logic behind this assumption is that the carbon released from biomass combustion originates from atmospheric carbon sequestered in plant tissues through photosynthesis, constituting a closed loop within the short-term carbon cycle. As such, biogenic sources of carbon differ from their fossil fuel counterparts where carbon is released from long held stores of carbon held underground. In the IPCC, this difference is highlighted by distinguishing fast domain reservoirs of carbon, where large fluxes of carbon are exchanged over relatively short periods of time, with the slow domain reservoirs consisting primarily of long held, geologically sequestered carbon where turnover times exceed 10,000 years or more [2].

While this assumption of carbon neutrality has been widely applied to GHG accounting schemes for bioenergy systems, the veracity of its application has recently been called into question, particularly for woody biomass sourced from forests [56-58]. The primary source of concern lies in the temporal lag between the release of carbon from biomass combustion and the subsequent sequestration from regrowth of the forest stand, often characterized as the carbon payback time [59]. Various accounting schemes have been developed in an attempt to better quantify the carbon dynamics of forest bioenergy including carbon debt [60], carbon payback time [59], and the use of counterfactuals (i.e. alternative fate of biomass as a point of comparison) [58]. While these accounting schemes often have a number of factors in common, there is no scientific consensus for which accounting framework is most appropriate. Also, arriving at such a conclusion may be impossible given the vast differences in carbon dynamics arising from different forest systems, management schemes, and assumptions about the alternative fate of carbon in the absence of bioenergy harvest [61].

For this study, the assumption of carbon neutrality for biogenic carbon is maintained with carbon payback time considered to be negligible. This assumption in the case of loblolly pine plantations in the southeast can be considered reasonable for several reasons: (1) Because of higher value, wood demand for timber products and pulp and paper dominate decisions to convert land to and from forest plantations, additionally forest residues for bioenergy supply supplemental income to land owners which potentially drives forest expansion [62]. (2) The rate of decomposition for downed woody debris is relatively high for softwood species in the southeast due to the warm, humid climate; reducing the potential for long term sequestration of carbon in dead wood. (3) Loblolly pine plantations have high growth rates and typically short rotation cycles, leading to much faster carbon payback time when compared to, for example, boreal or natural forests. For reference, Jonker et al. provide a detailed assessment of the carbon payback time for wood pellets produced from softwood in the southeast, concluding that under a landscape-level carbon debt approach, where existing softwood plantations are already in existence, “the issue of carbon payback is basically nonexistent” [63].

Plant level carbon accounting

Biomass is utilized at the FT plant at a rate of 1000 tonnes per day (dry basis). The carbon from the input feedstock is destined for one of four output streams – captured and compressed for CO_2 transport and injection, leftover in char, vented from the plant to the atmosphere, and incorporated into the Fischer-Tropsch fuels. Carbon accounting for Fischer-Tropsch synthesis with CCS is developed at the atmosphere-plant boundary:

$$C_{Net} = C_U + C_V + C_{FT} - C_{Bio}$$

Where C_{Net} is the overall daily emission of carbon, C_U is the carbon emission associated with upstream activities including silvicultural operations, harvest and transport, C_V is the carbon vented from the plant, C_{FT} is the carbon released from burning fischer-tropsch fuels and C_{Bio} is the carbon contained in the biomass feedstock. Biogenic carbon is counted as carbon sequestered from the atmosphere, hence the negative value assigned. Negative values for C_{Net} indicate negative emissions.

For scenarios where co-utilization of biomass and coal are considered, the carbon accounting framework is the same. When coal is incorporated significantly into the feedstock mix, net emissions become positive as the carbon released from the plant and the vent outpace the sequestration credit granted to biogenic carbon. For such scenarios a co-utilization ratio is defined by the portion of total input feedstock energy content (HHV basis) derived from biomass:

$$CUR = \frac{E_{HHV.Bio.}}{E_{HHV.Tot.}}$$

The higher heating value of coal and loblolly are 30.5 MJ/kg and 20.1 MJ/kg respectively. Biomass feed rate is held constant, therefore the amount of coal utilized increases proportionally as the co-utilization ratio decreases.

3.6 Water accounting Framework

Evaluation of the water consumption was carried out following the water footprint concept, originally introduced by Hoekstra [64], which provides a comprehensive indicator of both direct and indirect freshwater appropriation [53]. This study only accounts for direct water appropriation and does not consider indirect water consumption from fertilizer or fuel used in biomass supply chain. The overall water footprint for a process has three components – blue, green and grey water. Blue water consists of freshwater appropriation from surface water or groundwater resources, green water consists of rainwater appropriated for plant growth, and grey water consists of the volume of freshwater required to assimilate pollutants based on natural background concentrations and ambient water quality standards [53].

The hypothetical forest stand in question lacks a geographic explicit location represents a general case of loblolly pine plantation typical throughout the southeast. As such, the green water footprint was estimated using the Argonne National Laboratory's Water Analysis Tool for Energy Resources (WATER) Biofuel Water Footprint module. The module was run for soft wood using all feedstock types, with the state of Georgia selected as a reference region, calculating a green water footprint on a per mass basis of 128 Liters/kg. Loblolly pine plantations do not typically use any form of irrigation, therefore, the blue water footprint is assumed to be zero for feedstock production.

The grey water footprint for feedstock production was determined for the use of nitrogen fertilizer following the methods laid out in Hoekstra's water footprint assessment manual [53]:

$$WF_{grey} = \frac{(\alpha \times AR)/(c_{max} - c_{nat})}{Y}$$

WF_{grey} is the grey water footprint of nitrogen (m^3/tonne), AR is the chemical application rate (kg/ha), α is the leaching-run-off fraction determined to be 3.74% based on [65] as cited by [66], c_{max} is the maximum acceptable concentration, 10 mg/L, set by the EPA, and c_{nat} is the natural background concentration of total nitrogen present in streams in the southeast [52].

Water use for production of FT- fuels at the plant level was estimated based on results from the National Energy Technology Laboratories investigation of economic and environmental performance of different FT plant configurations [67]. These results are given as a ratio of water consumed divided by the fuel produced in the process. While this study has assumptions and configurations that are different than those specified in Liu et al. it was the only publication available that explicitly discussed water consumed at the plant level for Fischer-Tropsch synthesis. Water is assumed to be consumed at a ratio of 7.26 bbl of water for every bbl of FT product produced based on the BRW15 (bituminous coal and 15% biomass with recycle) configuration, which is the scenario most similar to the FTL configurations of Liu et al [34]. The results presented here for water consumption should be considered a rough estimation, as the water consumption is based on a plant configuration that is different than the one being modeled in the carbon accounting framework. Upstream water used for mining and transportation of coal is derived from Argone National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model [54].

CHAPTER 4

Results and Discussion

Overview

Resource implications for negative emission deployment via FT-CCS were estimated based on eight harvest scenarios developed for loblolly pine silviculture. A summary of the model outputs for one year of fuel production are presented in Table 7. A plant of this size can be expected to remove 0.1 MtC/year while producing 545 thousand barrels of fuel (63% diesel 37% gasoline) and supplying ~100 thousand MWh of electricity to the grid. Combined, this corresponds with ~3.42 PJ of total energy production annually. For reference, 3.05 PJ of fuel represents approximately 0.0106% of the U.S. and 0.34% of Georgia's transportation fuel consumption in 2015 [68]. In the same year, GHG emissions from the U.S. transportation sector totaled 492 MtCeq [69]. Results for land use intensity were highly variable based on the assumptions present in each harvest scenario. The estimated woodshed area required to deliver 1000 dry tonnes/d more than doubled from 128 to 297 thousand hectares, at the low and high extremes corresponding with SH30 and SL35 respectively. The total water footprint was proportionally dominated by green water (81.2% - 91.5%), followed by grey water (7.3% - 17.7%), and then process water consumed in the production of fuels (1% -1.2%). These results are further discussed later in the context of deployment at mitigation scale.

Table 7: Estimated resources impacts for one year of fuel production under BTL scenario with 1000 dt/d feedstock rate. Values in parentheses indicate mean averages across all scenarios. Negative emission potential is the amount of carbon removed. Land use refers to the land required to meet feedstock demand. Fuel produced is the volume of fischer-tropsch liquids generated. Energy in fuel refers to the total energy contained in the fuel produced. Exported electricity is surplus energy supplied to the grid, Green water is the volume of rainwater used to grow biomass, grey water is volume of water required to dilute fertilizer to background levels, process water is the volume water consumed at the FT plant, and the total water footprint is the sum of green, grey, and process water volumes.

Resource Impacts	*Value*	*Unit*
Negative Emission Potential	0.101 – 0.104 (0.102)	MtC
Land Use	128 – 297 (210)	kha
Fuel Produced	545	Mbbl
Energy in fuel	3.05	PJ
Exported Electricity	0.37	PJ
Green Water	46.7	Gigaliters
Grey Water	3.7 – 10.2 (6.91)	Gigaliters
Process Water	0.6	Gigaliters
Total Water footprint	51.0 – 57.5 (54.3)	Gigaliters

Rotation age at harvest affected the silvicultural emission factor and grey water footprint of delivered biomass, which is the source of variability in the estimation of the negative emission potential and grey water footprint. The total yield of wood increases with stand age, lowering the GHG emissions and nitrogen pollution allocated per unit mass delivered, Table 8.

Table 8: Impact of rotation age on silvicultural emission factor and grey water footprint associated with biomass cultivation. As rotation age increased from 20 to 35 years, yields increased 175%, emission factors decreased 50% and grey water footprint decreased 64%.

Scenario	*Total yield for one rotation (dry tonnes/acre)*	*Silvicultural emission factor ($kgCO_2eq/tonne$)*	*Grey water footprint ($m^3/tonne$)*
SL20/SH20	30.3	59.5	27.8
SL25/SH25	44.9	40.1	18.7
SL30/SH30	68.0	31.3	12.4
SL35/SH35	83.5	25.5	10.1

Compared to other carbon flows in the system, silvicultural emission factors exert a weak influence on the overall carbon balance of the system. Reducing the silvicultural emission factor from 59.5 $kgCO_2eq/tonne$ to 25.5 $kgCO_2eq/tonne$ for the BTL-CCS scenario results in a 3.4% increase in the net removal of carbon per day. Altering the grey water footprint of biomass has a stronger effect – a reduction from 27.8 to 10.1 $m^3/tonne$ results in a 64% reduction in the grey water footprint for finished FT liquids. Grey water footprint reduction from longer rotation ages is intuitive, as fertilizer application occurs less frequently when multiple rotations are considered.

Carbon balance

The daily net carbon balance for the BTL plant under the 20-year rotation age scenario in Figure 16 demonstrates how FT-CCS functions as a negative emission technology when biomass alone is used as a feedstock. For an ideal BECCS system, every molecule of carbon captured from photosynthesis would be sequestered geologically. In practice, this will never be the case due to a variety of carbon leakages inherent throughout the biomass supply chain as well as uncaptured carbon vented from the plant. From this perspective it is useful to define a carbon removal efficiency for NETs using biomass as the initial source of capture – the net carbon removed divided by the carbon from biogenic sources. The carbon removal efficiency of the BTL plant in figure 16 is 54.9%.

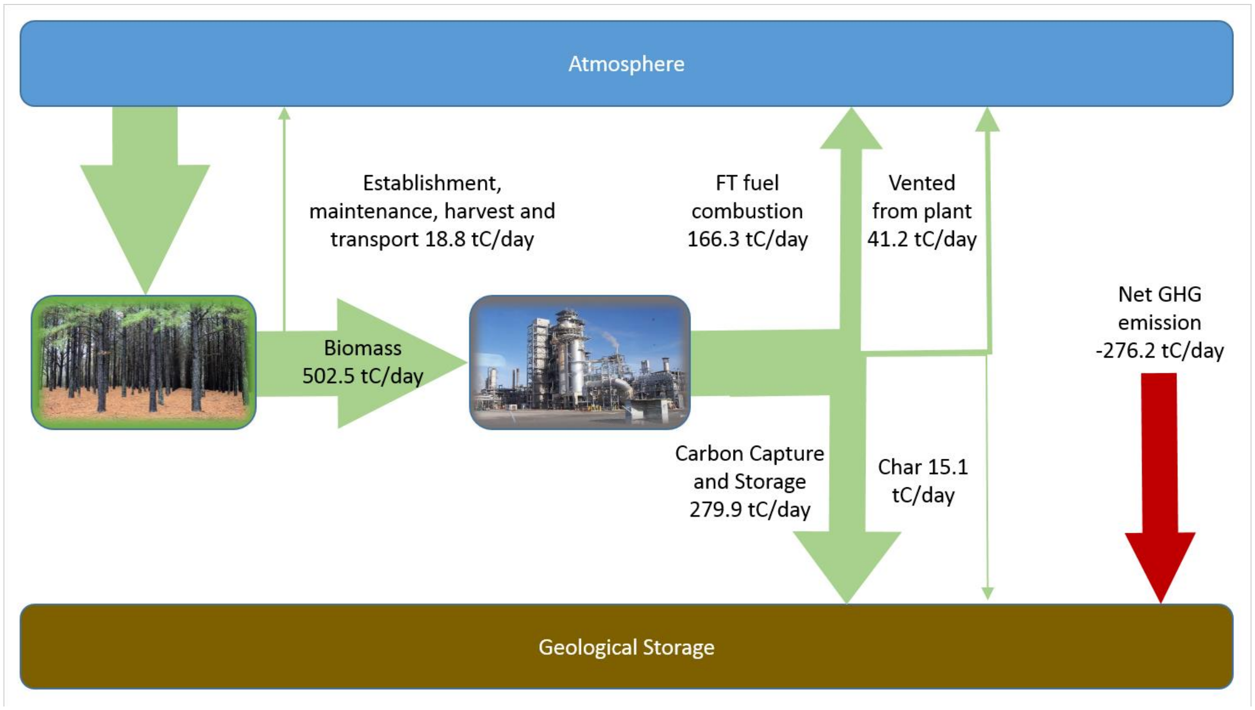


Figure 16: Equivalent carbon flow diagram for dedicated biomass FT plant. GHG emissions have been converted from CO_2 to carbon flows that have equivalent global warming potential.

Land Use

Estimation of land use was highly variable based on the intensity of harvest assumed in each scenario. Required woodsheds for all scenarios are shown in Figure 16. The effect of rotation age on biomass harvest inconsistent between high intensity and low intensity scenarios. Under the low intensity assumption, SL20 required the smallest woodshed due to thinnings and forest residues accounting for greater portions of available biomass. When greater portions of pulpwood harvest are allocated in the high intensity scenario, contribution of thinnings and residues are proportionally diminished, causing biomass availability to peak when the majority of the wood is classified as pulpwood. As the stand ages beyond this point, more trees grow into the saw timber classification explaining the increase in required woodshed area from SH30 to SH35.

Figure 17: Woodshed area required to deliver 1000 dt/d of woody biomass for eight different harvest scenarios.

Current allocation of pulpwood harvest for wood products in the region suggests that both harvest scenarios presented here are unlikely to be reasonable in the near-term. Even with the recent growth in wood pellet exports for European bioenergy, the vast majority of pine removals are utilized for timber and pulp-and-paper production. In 2014, 3.6 million tonnes of pellets were exported from the southeast to Europe accounting for 3.2% and 3% of total pine-pulpwood removals from the Atlantic and Gulf regions respectively [70]. Expansion of woody biomass harvest for energy is possible beyond what is currently utilized from southern pine plantations, however, the extent to which biomass harvest can be sustainably and economically expanded remains uncertain.

Other studies have estimated the potential biomass availability from pine timberland. Munsell and Fox investigated the feasibility for increasing woody biomass production from pine plantations in the US South, estimating up to 77.5 Tg of green wood available annually if 130,000 km^2 of existing pine plantations and 20,000 km^2 of pine plantations converted from idle farmland are placed under intensive management regimes for the production of a mixture of traditional wood products and woody biomass [71]. At this level of production, meeting the assumed feedstock rate of 1000 dt/d would require a woodshed of 140 kha, consistent with lower estimates for land use intensity produced in this model. Assuming 50% moisture content for green wood, this quantity of biomass could remove 10.6 MtC and produce 0.3 EJ annually, based on the FT-CCS system presented here. For reference, annual GHG emissions and energy consumption for the U.S. transportation sector totaled 492 MtCeq and 29 EJ respectively in 2015 [68, 69]. This provides a reasonable estimate for the maximum deployment potential of BECCS from southern pine plantations with FT-CCS given intensive silvicultural management regimes, and full development of biomass supply chain and CO2 transportation and injection infrastructure.

Water footprint

The water footprint for biofuels is often reported in terms of liters of water consumed per liter biofuel produced (l/l). The green, grey, and process water footprint of finished FT fuels were 538 l/l, 42 – 119 l/l, and 7.3 l/l respectively. This is in the same range, but slightly higher than other estimates for biofuel production from wood residue in the southeastern US. Yi- Wen investigated the water footprint of biofuels via mixed gasification of in the southeast and found average green, grey, and process water footprints for the region ranging from 400 – 443 l/l, 25 l/l, and 2.4 l/l respectively [66]. These differences can be explained by different assumptions, biofuel processes investigated, and the inclusion of hardwoods and SRWC, which typically use no fertilizer or have lower rates of application than pine plantations.

Co-utilization of coal and biomass

Co-utilization of coal and biomass together was also investigated. Daily carbon balance for a CBTL-CCS scenario with net positive emissions using a co-utilization ratio of 0.3 is shown in Figure 19. The addition of coal to the input feedstock increases the plant's capacity for producing fuels. However, as greater portions are added (i.e. decreasing co-utilization ratio), the potential for generating negative emissions is diminished until a breakeven point, at which the net emissions become zero and then carbon positive. The breakeven point for CBTL scenarios was found to occur at a co-utilization ratio of approximately 0.43 using the goal seek function in excel. The relationship between increasing utilization of coal, net carbon balance, and production capacity at the plant level is shown in Fig. 20.

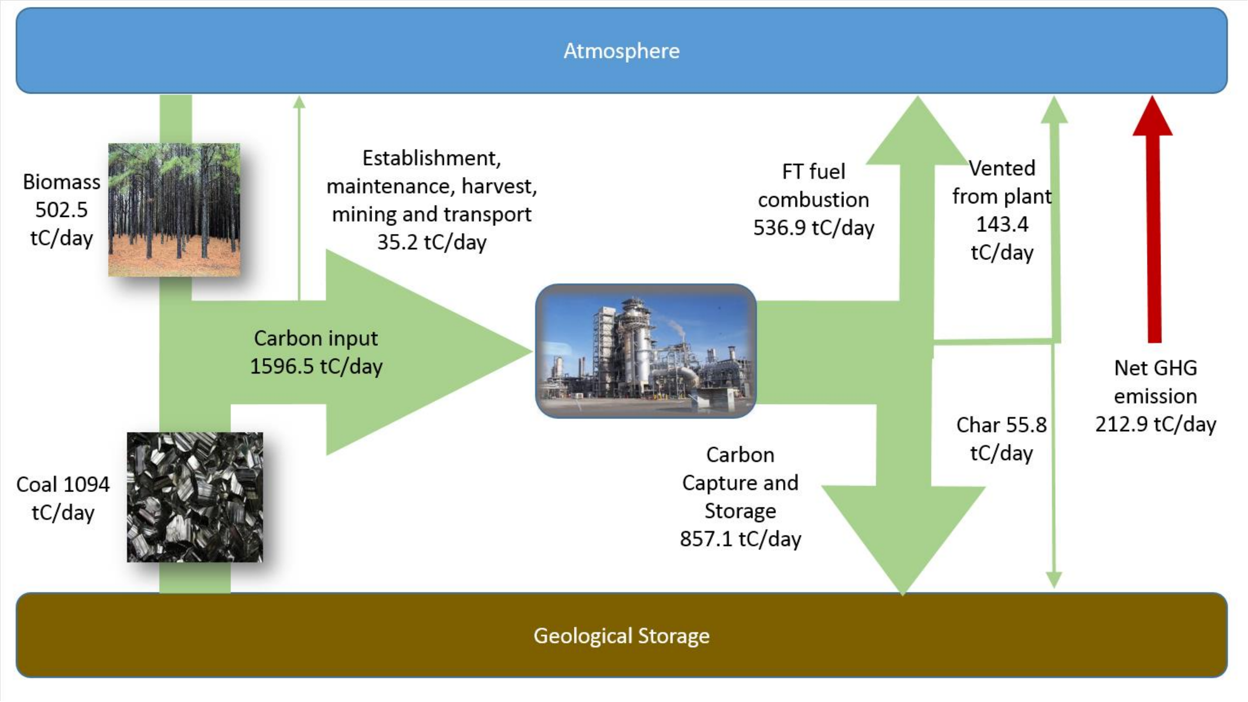


Figure 18: Equivalent carbon flow diagram for a CBTL plant with a co-utilization ratio of 0.3. GHG emissions have been converted from CO_2 to carbon flows that have equivalent global warming potential.

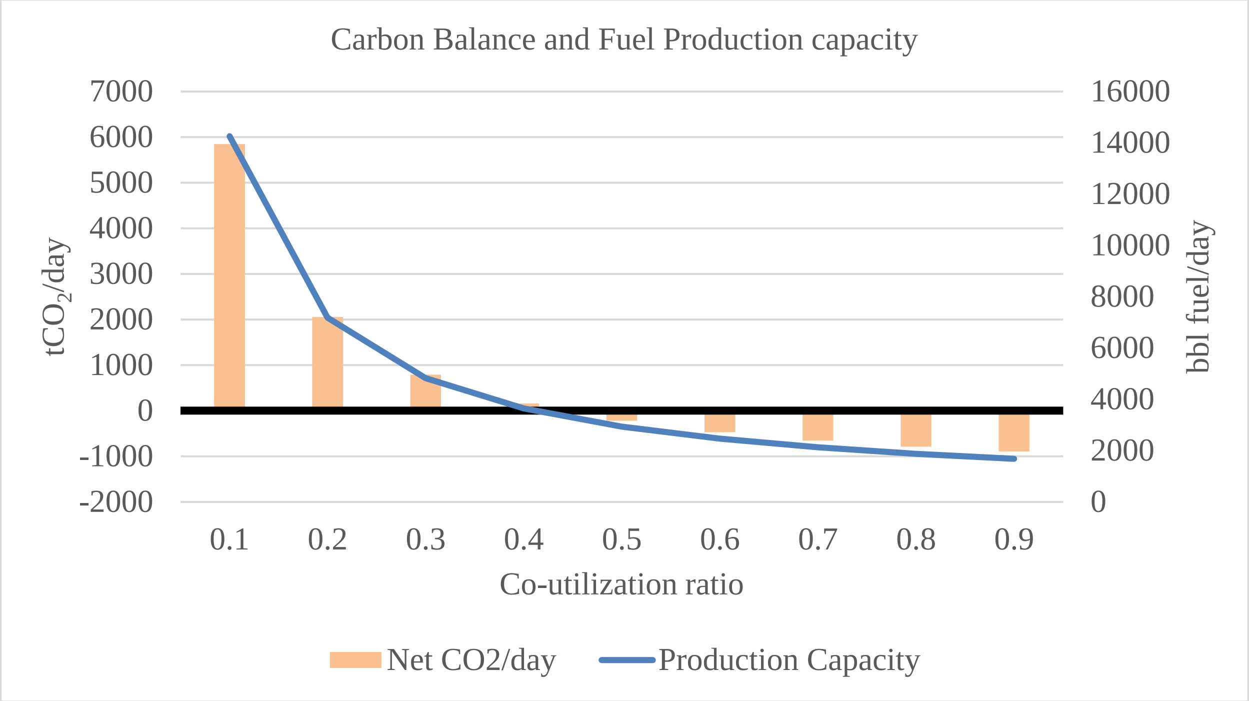


Figure 19: Relationship between carbon balance and increasing production capacity when coal is increasingly utilized for FT fuel production.

Resource implications at gigatonne scale

To assess the resource implications of FT-CCS at mitigation scale, evaluation of the system at the 3.3GtC/yr removal target provides a useful reference for comparison with other estimates of BECCS resource implications. Table 9 shows resource mobilization required to reach the 3.3 GtC/yr removal target for this study with other estimates from the literature. The values presented in each study provide a reference for discussion but are not necessarily congruent as the assumptions and configurations for each are different.

Table 9: Comparison of resource efficiency at 3.3GtC/yr removal target with other estimates from literature. Fajardy et. al provide estimates for two explicitly defined biomass supply chains for switchgrass from the U.S. and Miscanthus grown in Brazil and shipped to the UK. The study by Smith et. al was not location or biomass specific. Total land estimates are not equivalent since energy crops are grown on land dedicated soley for bioenergy whereas plantation silviculture produces a mixture of wood products along with biomass for energy. An adjusted land estimation is given in brackets that weighs land requirement based on allocation of total yield for bioenergy. Energy estimates in Fajardy et. al subtract biomass supply chain energy from supplied energy, which is not considered in Smith et. al or this study. The water footprint estimates in Smith et. al were calculated relative to a counterfactual grassland, while Fajardy et al. and this study consider total water allocated for evapotranspiration. Values in parentheses indicate average case. Negative values for energy indicate energy supplied.

	This Study	*Fajardy et al. 2017 (switchgrass U.S.)[72]*	*Fajardy et al. 2017 (miscanthus Brazil)[72]*	*Smith et al. 2016[7]*
Biomass (Gt_{DM}/yr)	11.9	9.2 – 13.1 (11.1)	9.0 – 15.5 (10.5)	–
Land (Mha)	4100 – 9500 , [1790 – 3130]	1245 – 2392	363 – 943 (538)	380 - 700
Energy (EJ/yr)	- 109	-22.4 to 1.0 (-15.1)	-15.3 to 37.0 (-0.01)	-170
Water (Tm^3/yr)	1.64 – 1.72	7.8 – 15.7 (10.4)	9 -15.5 (10.5)	0.72

Both referenced studies estimate BECCS deployment via steam turbine with post-combustion CCS utilizing energy crops as the source of biomass feedstock. This study is in good agreement with Fajardy et al. in the case of dry biomass required for negative emission deployment [72].

The land use intensity for woody biomass from loblolly pine plantations is massive compared with energy crops. Providing the necessary feedstock to meet the 3.3Gt/yr removal target under the high intensity harvest scenarios modeled would require a land mass roughly equivalent to the total area of forested surface on the planet. The large difference in land use intensity is explained by the differences between production of biomass from energy crops and from timberland. Plantation silviculture produces multiple streams of wood products for use, while energy crops grown on marginal land are dedicated solely to bioenergy. Accounting for these differences could be addressed by modeling the carbon dynamics of the entire forestry production chain in parallel with forestry based BECCS systems, such that sequestered carbon from wood products in buildings and landfills is accounted for in overall carbon balance. Harmonizing carbon flows and reservoirs from stand inventory, wood products, and BECCS would provide a more complete picture of the negative emission potential for the whole system, given multiple use streams for the land that produces the biomass.

Another approach is to weigh the land requirement with the fraction of total yield allocated for bioenergy in each scenario. For the range of harvest scenarios considered, the portion of total yield allocated for bioenergy ranged from 19% - 72%. When land use is allocated based on this fraction, the land use intensity is reduced to 1790 Mha in the lowest case SL35, where 19% of the total yield is allocated for energy, and 3130 Mha in the highest cases SL20 and SH20 where 34% and 72% of the total yield are allocated for energy respectively. This provides a better point of comparison for energy crops as the additional land used for alternative wood products isn’t considered. Even with the reduction in land use estimation, biomass from loblolly plantations requires more land than energy crops to achieve the same negative emission potential.

The two referenced studies approach energy generation using a different framework. The energy estimate from Fajardy et al. subtracts the biomass supply chain energy consumption from the energy generated by the BECCS system, which was not considered in Smith et al. or this analysis [7, 72]. Switchgrass and miscanthus in Fajardy et al. are sourced from the U.S. and Brazil with supply logistics including grinding, pelletizing and long distance transport to the UK [72]. Without the energy penalty from biomass supply chain, Fajardy et al reports 170 EJ of energy supplied by the BECCS system [72]. Given the substantial reduction in energy produced when the supply chain penalty is applied, biomass supply logistics should be optimized to reduce energy consumption to the greatest extent possible. This highlights the need for colocation of biomass supply with suitable storage sites to minimize embodied energy of biomass.

There is high variability in the estimates for water consumption between the two studies referenced here. These differences arise primarily from the assumptions made in the calculation of the green water footprint and, to a limited degree, the choice of cooling tower configuration [72]. In Smith et al., the green water footprint is calculated with respect to a reference grassland, or counterfactual, that is assumed in the absence of bioenergy harvest [7], while Fajardy et al. estimate the water footprint based on the total evapotranspiration appropriated for the production of energy crops [72], leading to a much higher value. Green water footprints are highly variable based on the region and source of biomass feedstock. For this study, no counterfactual is used and green water footprint represents the total evapotranspiration for growing forest biomass. Results from this study only include direct water consumption and do not account for indirect water consumed in the production of fertilizers and fuels used in the biomass production and supply chain. These results indicate that bioenergy from forest biomass has a substantially lower water footprint compared with energy crops and agricultural residues, consistent with other water footprint estimates in the literature [66, 73, 74].

Limitations and shortcomings

This model, although providing reasonable first estimates, has a number of limitations. Depending on the biomass logistic system employed, carbon leakages along the supply chain such as off-gas emissions from biomass storage or additional transportation emissions in the case of higher procurement radius may be underestimated. I was unable to find useful LCA information about the energy and carbon emissions embodied in the construction and operation of CO_2 transportation pipelines, which was not accounted for in this analysis. The estimation for water consumed in fuel production at the plant level was based on a water consumption factor derived from a different design configuration than what the carbon and fuel production model is based on. Additionally, energy consumed in the harvest and transport of biomass is not accounted for, which should be subtracted from estimations of energy generation to have a more accurate estimation of net impact on energy sources. Also, because forests provide multiple product streams, modeling carbon dynamics of BECCS in parallel with carbon sequestered in wood products and live stand inventory would provide a more complete picture of the overall system performance. With more time and resources these are all points of consideration that would aid in the further development of this model and future work.

Chapter 5

Conclusion

A modeling tool was developed in Microsoft Excel in order to estimate the land-use, energy, and water resource impacts of negative emission deployment through FT-CCS using forest biomass from loblolly pine plantations under management conditions typical to the southeastern United States. When compared at the 3.3GtC removal target, the water footprint of forestry based FT-CCS was found to be lower than previous resource estimates for BECCS deployment using energy crops, while energy production was reduced by 46%. One major point of difference was determined in the case of land requirement.

Land requirement for FT-CCS with loblolly pine was highly variable under the range of harvest scenarios investigated, but in all cases land use intensity was much higher than estimations in literature for energy crops grown on marginal lands. These estimations are not necessarily congruent as fuel wood is one of several products produced from plantation silviculture, while energy crops are grown for a single use. Additionally, trees grown in timberland can provide multiple pathways for carbon sequestration through the production of long lived wood products and carbon sequestered in live stand inventory. To account for these differences, the carbon dynamics of the entire biomass production chain from pine plantations, modeled in parallel with a given BECCS system would provide a more complete view of system performance and carbon negativity than what is presented here. Accounting for carbon stored in the live stand inventory would help to ensure sustainable rates of biomass harvest and validation of carbon removal.

The capacity for southern pine plantations to provide adequate biomass for large scale BECCS deployment remains uncertain. The harvest scenarios presented here allocate greater portions of biomass than what has been historically utilized for existing wood pellet production. In practice, management decisions associated with plantation silviculture are driven by market forces. As such, and availability of forest biomass for BECCS will be constrained by the competing price for wood products in timber markets, subsidies provided for carbon removal, and capacity for colocation of biomass supply with suitable storage sites for CO_2 injection. Given the relatively large land footprint estimated here, it is unlikely that forest biomass will be suitable for large-scale BECCS deployment, though it may provide supplemental feedstock particularly in regions where pine plantations are abundant and potential for co-location with CO_2 injection exists.

Ultimately, there is no technical solution that provides a silver bullet for the climate crisis. While technologies such as the FT-CCS system modeled here can help by removing carbon from the atmosphere and substituting fossil fuels, the capacity and rate at which they do so will be constrained by biophysical resources they rely on to operate. Rapid decarbonization of human civilization will require a multi-faceted approach that relies on a portfolio of mitigating options including renewable energy incorporation, improvements in energy efficiency, deployment of NETs, and reducing energy consumption. Accounting for the resource base upon which all of these strategies lie can help to make informed decisions about future pathways for actualizing these goals.

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