DISSERTATION

INTEGRATED TECHNO-ECONOMIC ANALYSIS AND LIFE CYCLE ASSESSMENT OF EMERGING TECHNOLOGIES WITH TEMPORAL RESOLUTION

Submitted by

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ABSTRACT

INTEGRATED TECHNO-ECONOMIC ANALYSIS AND LIFE CYCLE ASSESSMENT OF EMERGING TECHNOLOGIES WITH TEMPORAL RESOLUTION

Techno-economic analysis (TEA) and life cycle assessment (LCA) are analytical tools used to quantify the economic and environmental performance of emerging technologies. TEA and LCA help guide the development of these technologies by identifying areas where additional research will significantly reduce economic costs and environmental impacts. Although often used in tandem, TEA and LCA output separate results that rely upon disconnected metrics. When considering the impact of time, the disconnect between TEA and LCA methods is critical and can significantly impact results. In this dissertation, three phases of research are conducted to illustrate and reconcile the disconnect between TEA and LCA. In the first phase, standard TEA and LCA methods are used to evaluate the economic and environmental performance of natural rubber derived from guayule (*Parthenium argentatum*). This evaluation is used to identify the strengths and weaknesses of interpreting disconnected TEA and LCA results. In the second phase, two new methods are created to overcome this disconnect by integrating temporally resolved TEA and LCA. These methods are applied to electric power and guayule rubber production to highlight the impacts of integrating temporally resolved TEA and LCA. In the third phase, integrated TEA and LCA is used to perform a deep-dive evaluation on low-emissions technology options for natural gas combined cycle power plants. In this phase, TEA and LCA with temporal resolution are used to identify cost targets for biomethane, carbon capture and storage (CCS), and bioenergy with CCS (BECCS) under different emissions pricing scenarios. Taken together, the three phases of research in this dissertation represent a wide range of applications and methodologies, each with varying objectives and complexity. Understanding the details of these approaches will help guide future analysis where economic costs, environmental impacts, and time are important considerations in technological development.

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CHAPTER 1: INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) special report on global warming of 1.5°C highlights the need for mitigating greenhouse gas emissions while simultaneously adapting to meet the risks of near term climate change[1,2]. These large-scale challenges have encouraged technological development with a large number of novel technologies emerging in sectors such as agriculture, energy, and transportation. The feasibility of using these technologies to mitigate and adapt to climate change is highly dependent upon their economic and environmental performance. Gauging this performance requires unique analytical tools such as process modeling, techno-economic analysis (TEA), and life cycle assessment (LCA). Each of these tools uses quantitative methods to evaluate performance and identify critical areas for further research and development. While these tools are generally coupled together through common process modeling assumptions, comparing the output results of TEA to those of LCA can be challenging, as these tools use entirely different methods and metrics to evaluate performance.

TEA methods are built largely upon the foundational concepts of engineering economics[3]. Within TEA, a temporally resolved cash flow is developed to track the costs and revenue of a specific technology over its estimated lifetime. While TEA can be applied to any technology, it is frequently used to evaluate large-scale production facilities such as biofuel refineries and electric power plants[4,5]. Within these facilities capital costs include acquisition of land and construction of facilities, as well as the purchase and installation of process equipment. Operational costs include fixed costs such labor, insurance, and maintenance, along with variable costs such as electricity, fuel, and any other materials consumed within the facility. Other annual considerations include taxes, depreciation, and loan financing. The revenue considered within a TEA includes the sale of a primary product and any co-products resulting from secondary material flows leaving the production facility. For example, the production of biofuels through pyrolysis generates a waste stream of bio-char that can be sold as a fertilizer co-product, increasing the annual revenue of the biofuel production facility[6].

Within the TEA, the costs and benefits of the technology can be analyzed to determine a range of economic metrics such as internal rate of return, payback period, return on investment, or minimum product selling price. The particular metric used to evaluate economic performance varies and is dependent upon the intent of the analysis. Regardless of which metric is selected, the element of temporal resolution plays an important role within TEA. This role is defined by the well-established time value of money driven by concepts such as inflation and time preference. Within TEA, discount and interest rates are dependent upon this time value, ultimately having a significant impact upon the expected economic performance of a technology.

Unlike TEA, LCA methodology does not consider economic costs or revenue. Instead, LCA focuses on physical flows into and out of a technological system. Flows into the system include energy sources such as electricity and fuels, along with materials like water, chemicals, metal, or concrete. Flows out of the system include the final products of the system and any emissions to the environment, which in many cases cause some form of negative environmental impact. These emissions are typically lumped together into a range of environmental impact categories. The categories used within LCA are dependent upon where the study is being conducted, as different countries utilize different methods. In the United States, the Environmental Protection Agency has defined the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) which currently includes ten impact categories, one of which is global warming potential due to greenhouse gas emissions[7]. Within standard LCA methodology, tracking energy and materials to determine these environmental impacts does not include temporal resolution. Instead, all emissions categorized within TRACI are averaged over the lifetime of a technology, effectively removing any consideration of when emissions occur.

Even from brief introductory descriptions, it is apparent that a number of major differences exist across TEA and LCA, limiting their usefulness when applied in parallel. In this work, I will narrow the range of differences down to two primary considerations. First, the final metrics of TEA do not align with the final metrics of LCA. For example, there is no way to directly compare a kilogram of carbon dioxide emitted to a dollar of cost or revenue. Therefore, while TEA and LCA can be used to evaluate a technology, the results of the two analyses cannot be directly coupled. Second, LCA excludes temporal resolution, putting it in direct conflict with TEA where costs and benefits are weighted as a function of when they occur. Any temporal changes within a technology will have no impact on LCA, as emissions are considered equivalent regardless of when they are emitted. As demonstrated in later sections, this omission of temporal resolution, is inadequate and represents a major limitation of LCA.

In light of these two major disconnects, this dissertation is focused on understanding and improving upon existing methods to allow for integrated TEA and LCA analyses of emerging technologies. The three research phases included in this work are: 1) An integrated analysis of an emerging guayule rubber production facility using standard TEA and LCA methods, 2) Development of two new methods for better integrating TEA and LCA analysis using the social costs of greenhouse gases, 3) Evaluation of low-emissions technology options for an existing natural gas combined cycle facility using new integrated TEA and LCA methods. The following three chapters will explain the background information, methods, and major findings of each of these three research phases. The findings demonstrate the importance of using combined TEA and LCA to identify the economic and environmental performance of emerging technologies that are proposed for mitigating and adapting to climate change.

CHAPTER 2: INTEGRATED TEA AND LCA EVALUATION OF GUAYULE RUBBER[a]

2.1. Background

The economic and environmental performance of an emerging technology can greatly benefit from an integrated TEA and LCA evaluation. In this research phase integrated TEA and LCA were used to evaluate the emerging technology of guayule (*Parthenium argentatum*) rubber production. Guayule is a drought tolerant shrub native to the southwest United States and northern Mexico that has long been known as a viable source of natural rubber[8]. Guayule's high natural rubber content, typically 8-12% by mass, makes it a promising alternative to traditional rubber sources such as petroleum and Hevea trees[9]. The relatively high value of natural rubber and the wide range of corresponding products such as tires, medical equipment, and performance sports apparel (wetsuits, waders) have the potential to generate significant revenue[10–12]. Furthermore, other non-rubber portions of the guayule plant include a resin and the remaining lignocellulosic biomass commonly referred to as bagasse. The resin has the potential to be further processed into products such as pesticides, adhesives, or wood coatings. The bagasse can be utilized on-site to reduce utility demand or converted into an additional co-product such as liquid biofuel[13–15]. The potential for revenue, along with guayule's drought tolerance makes the plant an ideal candidate for adoption in the southwest United States, where a growing population and the uncertainty of future climate conditions is presenting significant risk to regional agriculture[16,17].

Despite guayule's promising physical characteristics, its economic viability in the southwest United States remains uncertain. While renewed interest in guayule has led to some recent economic analysis, it has been limited to the conversion of guayule bagasse to fuels and the feasibility of rubber production within Mediterranean Europe[13,18]. Prior to this work, an earlier effort reviewed the costs of guayule rubber production within the United States[19]. However, this analysis is outdated and does not

[a] This chapter has been published as a peer-reviewed journal article: Sproul, E. et al. Integrated techno-economic and environmental analysis of guayule rubber production. Journal of Cleaner Production 273, 122811 (2020).

include current data from improved agricultural and rubber extraction processes[20–24]. Capturing these agricultural and rubber extraction processes in an up to date TEA is essential to understanding guayule's potential for success in the desert southwest, as well as identifying critical areas for investment to move towards commercialization.

In addition to a TEA, there is a secondary need for a thorough LCA of guayule rubber production. Using LCA to understand environmental impacts will allow for a comparison to other synthetic and natural rubber sources. Furthermore, it provides an opportunity to reduce the environmental impacts of guayule rubber by identifying critical areas for further research and development before production is rolled out at full-scale. Recognizing these opportunities, previous researchers have explored the environmental impacts of guayule, including a detailed sustainability review, comparison of guayule irrigation practices, and a full LCA of a guayule rubber tire[9,25–27]. Across these publications, a large amount of data exists for the agricultural production stages, but far less data exists for downstream guayule rubber extraction. In the most recent work, Eranki et al. estimated industrial scale rubber production based on an experimental solvent extraction batch process[27]. While this work is the only publicly available post-harvest LCA of guayule, it is limited in its analysis. For example, future industrial extraction facilities are expected to utilize a continuous solvent extraction process. This type of rubber extraction process has yet to be evaluated. Understanding the environmental impact of guayule rubber production at full-scale requires modeling this continuous process.

The work in this chapter addresses the shortcomings of previous guayule analyses while also providing a new perspective based on integrated TEA and LCA. The novel innovative contributions of this work are: 1) a process model that tracks all materials and energy required for present day cultivation, transportation, and extraction of guayule rubber in the southwest United States, 2) the first integrated TEA and LCA of guayule rubber production, and 3) the identification of parameters where further research and development will reduce costs and environmental impacts. These outcomes are critical for assessing the current state of guayule rubber production, while also providing guidance for the future development of guayule in the southwest United States. In addition, they demonstrate the advantages and limitations of using the disconnected metrics of TEA and LCA to evaluate an emerging technology.

2.2. Methods

The methods of this work are broken into three sections. The first section details the development of a process model that tracked the materials and energy required for guayule rubber production. The second and third describe how this process model was used to concurrently inform TEA and LCA. All process modeling and analyses were developed in Microsoft Excel using Visual Basic for Applications routines to automate calculations.

2.2.1. Process Model

The process model for guayule rubber production consisted of agricultural, transportation, and rubber extraction processes. These processes were integrated together in the process model to track cumulative material and energy demands of producing rubber, resin, and bagasse from a guayule feedstock. The process model system boundary began with field preparation for planting and ended with final production of guayule rubber and co-products. Table 2.1 highlights key input parameters used within the process model. A full detailed list of input parameters for the process model can be found in Tables A1-A3 of the appendix of this document. A process model diagram with a system boundary is shown Figure 2.1.

Table 2.1. *Key input parameters for process model across agriculture, transportation, and rubber extraction processes.*

Key Modeling Input Parameters		
Single farm size	500	hectares
Guayule adoption	75	hectares/farm
Harvest yield	30	metric tons/hectare
Rubber fraction	0.075	kg rubber/kg biomass
Resin to rubber ratio	0.65	kg resin/kg rubber
Transport distance	44.27	km (farm to extraction facility)
Extraction input capacity	500,000	metric tons of guayule/year

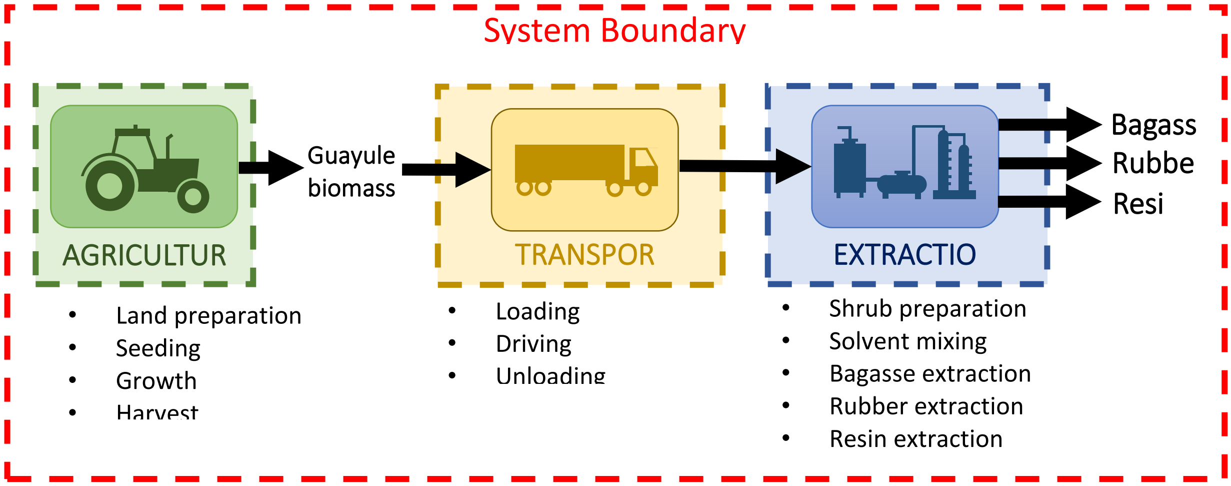

Figure 2.1. *Process model diagram of guayule rubber, resin, and bagasse production. System boundary ends at the gate of the extraction facility.*

2.2.1.1. Agricultural Process

The first process of the model included all operations required to produce guayule biomass, including land preparation, planting, growing, and harvesting. Within the process there was detailed accounting of material flows such as irrigation water, fertilizers, and herbicides. From these flows, the model identified the required labor and equipment, along with corresponding energy demands in the form of fuels and electricity. The current agricultural process was modeled to represent a 500-hectare farm located in central Arizona. This size was based upon the average farm size from the United States Department of Agriculture's 2018 National Agricultural Statistics for Arizona[28]. The modeled farm included guayule, along with other crops such as cotton, field corn, sorghum, barley, wheat, and alfalfa. The adoption of guayule was an adjustable input parameter and was set at 15% (75 hectares) of the farm for the baseline analysis. A full list of major parameters used for the agricultural process is shown in Table A.1 of the appendix.

The agricultural process included a six-year guayule growth cycle. The first year of the cycle is an establishment year, meaning it includes land preparation, planting, growth, and intensive weed control until the crop has full cover. The second year is a harvest year, which includes further growth and the initial harvest of the guayule crop. When guayule is harvested in the second year, it is cut just above the ground with the root system left in the ground as a starting point for regrowth. In year three and four the shrub is regrown and harvested a second time, and years five and six repeat this pattern once more. The third harvest in year six marks the end of the growth cycle. In year seven the land is reworked and replanted, marking the beginning of a new cycle. While guayule yield does vary across different cultivation conditions, the baseline parameter used in all three harvest years was thirty metric tons per hectare with an assumed rubber fraction of 0.075 kg rubber per kg guayule biomass. These input parameters were based upon experimental data, as well as correspondence with industrial partners, and fall within the wide range of existing results and future targets for guayule rubber production reported in literature[9,29].

2.2.1.2. Transportation Process

In the transportation process of the model, harvested biomass was transported from the farms to a rubber extraction facility via short haul trucks with trailers. Total truck and trailer weight were modeled at 36,287 kg, including a 20,412 kg payload capacity. Using the information in Table 2.1 and geographic information system data, the average distance from the farms to an optimized processing facility location was modeled at 44.27 km. A map of this facility location and surrounding farmland suitable for guayule production in Arizona's Maricopa and Pinal counties is located in Figure A.2 of the appendix. Although the transportation distance was based on expected guayule farmland and a rubber extraction facility location in Arizona, it also aligns with transportation distances for well-established biorefineries such as corn ethanol production in the states of Iowa and Ohio[30]. Given a transportation operating window of eight hours per day, the model required fifteen trucks to meet the twenty-four-hour demand of the rubber extraction facility. Other transportation considerations included fuel efficiency, loading and unloading time, and average speed. A full list of transportation input parameters is located in Table A.2 of the appendix.

2.2.1.3. Rubber Extraction Process

The third and final process in the model was a continuous rubber extraction process required to generate rubber, resin, and bagasse from the harvested guayule shrub. The model tracked the use of materials such as solvents, water, and mineral oil, along with energy in the form of natural gas and electricity. Process data was based on an existing pilot scale facility located in Arizona, as well various publications and patents[10,22,23]. Material and energy flows were linearly scaled by mass throughput so that the model represented a full-scale facility with an input capacity of 500,000 metric tons of guayule biomass per year. The process was based on dual solvent extraction using hexane and acetone to dissolve rubber and resin, respectively. Solvent recovery was modeled in multiple distillation steps leading to overall solvent recovery efficiencies of 98.5%. Other critical input parameters considered were guayule rubber and resin content, solvent mixing ratios, and equipment efficiencies. A full list of rubber extraction input parameters and a process diagram can be found in Table A.3 and Figure A.1 of the appendix.

Beyond the fundamental equipment required for rubber extraction, there were two other major modeling considerations within the rubber extraction facility. The first consideration was heat integration across the solvent recovery processes. In the model, heat exchangers reduced the high outlet temperatures leaving the recovery process by preheating the solvents, mineral oil, and water that are entering the recovery process. This reduced the consumption of natural gas required to heat flows into the recovery process and reduces the need to cool outlet flows. The effectiveness of each heat exchanger was assumed to be 85%. The second modeling consideration was the generation of on-site heat and power by combusting bagasse in a combined steam boiler and turbine system. Within the model this on-site heat and power scenario was used to burn bagasse in place of natural gas and gird electricity. In this scenario, the overall efficiency of heat generated by the steam boiler was modeled at 70%, while the overall efficiency of electricity generated by the turbine was modeled at 20%[31]. A list of inputs for the on-site heat and power system can be found in Table A.9 of the appendix.

2.2.2. Techno-Economic Analysis

The materials, energy, and equipment tracked through the process model of Section 2.1 were used to inform capital and operational costs for guayule rubber production. With this data, the TEA was broken into two separate components. In the first, the agricultural costs were used to determine the minimum selling price of guayule biomass to recover all costs of growing guayule for six years. In the second, this guayule biomass cost, along with transportation and rubber extraction costs, were used to determine the minimum rubber selling price that would recover all production costs across the full system. The common guayule biomass selling price across the agriculture and rubber extraction processes were used to integrate the farm and rubber extraction facility into a single TEA.

2.2.2.1. Agriculture Economics

At the farm level, a cost benefit analysis was performed over the six-year guayule growth cycle. Agriculture costs included material and energy inputs such as fertilizer, herbicides, water, and electricity. In addition, the analysis included farm equipment and related costs such as fuel, repairs, maintenance, replacement, and labor. A full list of costs used in the baseline scenario is included in Tables A.4-A.6 of the appendix. Due to the six-year time frame, it was necessary to discount future costs back to their present value using a discount factor. The baseline discount rate defined for the farm was 6%. This discount rate and other parameters used for the baseline agriculture economic analysis are listed in Table 2.2. With these parameters, the agriculture economic analysis was solved to find the minimum selling price of the guayule biomass that would allow revenue to recover all guayule agriculture costs over the six-year growth period of the crop.

2.2.2.2. Rubber Extraction Economics

The minimum selling price of guayule biomass from the farm also represents the minimum biomass purchase price for the rubber extraction facility. This biomass cost was combined with other operating costs, capital costs, transportation costs, and product revenues into a single TEA for the full 30-year lifetime of the rubber extraction facility. The TEA was built around a set of standard parameters based on previous bioprocessing publications[4,32–34]. All process facility costs are shown in Tables A.7 and

A.8 of the appendix with key parameters used in the TEA presented in Table 2.2 and 2.3. The rubber extraction TEA was solved to find the minimum selling price of rubber that would yield a total net present value of zero at the end of the thirty-year life time. This minimum selling price represents the revenue needed to recover all costs of production including agriculture, transportation, and rubber extraction while meeting the economic parameters outlined in Table 2.2 and 2.3.

Table 2.2. *Input parameters for agricultural economics.*

Agriculture Economic Input Parameters	
Discount rate	6%
Miscellaneous and overhead as a percent of cash costs	5%
Operating interest rate for harvest operations	8%
Operating interest rate for production inputs	8%
Duration of harvest loan	6 months
Duration of operating loan	6 months

Table 2.3 *Input parameters for rubber extraction economics*

Rubber Extraction Economic Input Parameters	
Rubber Extraction Facility Loan and Investment	
Internal rate of return	10%
Equity	40%
Loan interest	8%
Loan term	10 years
Rubber Extraction Facility Construction	
Working capital	5%
Construction period	3 years
Construction completed year -2	10%
Construction completed year -1	50%
Construction completed year 0	40%
Rubber Extraction Facility Start Up	
Startup time	0.5 years
Production during start up	50%
Rubber Extraction Facility Taxes and Depreciation	
Tax rate	35%
Depreciation	7 year MACRS

2.2.2.3. Scenarios and Sensitivity in TEA

Recognizing that the minimum selling price of rubber is dependent upon co-products, two different co-product scenarios were analyzed. The first was the baseline scenario where co-product revenue is generated by selling bagasse at \$0.10 per kg and resin at \$1.00 per kg. These co-product values align with a previous analysis when adjusted for inflation to 2020 US dollars[19]. The second scenario used the bagasse to generate on-site heat and power, instead of selling bagasse as a co-product. In this scenario, the capital cost of the on-site heat and power system (including installation, indirect, and contingency costs) was estimated at \$1300 per kW of combined heat and power capacity[35]. Maintenance of the system was estimated at 3% of the capital cost and labor included eight additional shift operators. In situations where bagasse production exceeded the heat and power requirements for rubber extraction, excess electricity was treated as a co-product and was sold back to the grid at a rate of \$0.05 per kWh. This rate is relatively conservative when compared to current rates offered to Arizona power customers with on-site solar installations[36]. In the on-site heat and power scenario, the value of resin was kept at \$1.00 per kg.

The final component of the TEA was a sensitivity analysis. The sensitivity analysis was performed by varying 147 individual input parameters by ±20%. As each parameter was varied, the new minimum rubber selling price was recorded. Once the results of all parameters were recorded, the list was sorted to identify the individual input parameters that have the largest impact on the economic results of the model.

2.2.3. Life Cycle Assessment

2.2.3.1. Scope and Data of Life Cycle Assessment

Similar to the TEA, the environmental analysis was informed by the process model outlined in Section 2.1. The environmental analysis focused on identifying the cradle-to-gate environmental impacts of guayule rubber production via LCA methods[37,38]. Emissions due to upstream materials and energy (i.e. those that were consumed throughout the supply chain) were obtained from ecoinvent 3.4 and the United States Life Cycle Inventory database[39,40]. A full list of life cycle inventory data can be found in Tables A.10 and A.11 of the appendix. Per standard LCA cut-off methods, the environmental impacts embodied within capital infrastructure (e.g. steel, concrete) were excluded from this analysis due to their minimal impact when spread over a thirty-year operational period[38]. However, embodied emissions were included for farm equipment as the lifetime of this equipment is often far less than thirty years, making the embodied impacts more significant. Cumulative emissions for guayule rubber production were grouped into ten categories of environmental impacts via the United States Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1[7].

2.2.3.2. Scenarios and Allocation in Environmental Analysis

Within the environmental analysis, the baseline and on-site heat and power scenarios were both considered. In the baseline scenario the environmental impacts of rubber, resin, and bagasse were summed to generate a total system environmental impact. Within the on-site heat and power scenario, bagasse is combusted to replace natural gas and grid electricity consumption. In addition, any excess electricity from bagasse was modeled to displace standard grid electricity, resulting in an environmental impact credit that was applied to the overall rubber and resin production process. Estimating the individual environmental impacts of rubber, resin, and/or bagasse required allocating some portion of the total environmental impact to each product.

While allocation helps isolate the impacts of specific products, it can also significantly alter results, leading to different conclusions. As a result, two forms of allocation were applied to present two separate perspectives. The first was mass allocation, which distributes the share of environmental impacts across products based upon the overall mass of each product. The second was economic allocation, which distributes the environmental impacts based on the economic value of each product. While economic allocation is accompanied by uncertainty, it is considered a common practice in LCA when other methods such as expansion of the system boundary are not an option[41]. In addition, it has been found as a valuable form of analysis when co-products have significantly different economic values, as is the case with guayule rubber, bagasse, and resin. Mass and economic methods for allocating the environmental impacts to a specific product are shown in Equations 2.1 and 2.2, respectively.

$$Environmental\ Impact_{mass,p} = (Environmental\ Impact_t)\frac{Mass_p}{Mass_t} \quad \textbf{\textit{(2.1)}}$$

$$Environmental\ Impact_{economic,p} = (Environmental\ Impact_t)\frac{Economic\ Value_p}{Economic\ Value_t} \quad \textbf{\textit{(1.2)}}$$

In Equation 2.1, a portion of the total (t) environmental impact of the system is allocated to a specific product (p) based on the product's mass relative to the total mass of all products. In Equation 2.2, a portion of the total environmental impact of the system is allocated to a specific product based on the product's economic value relative to the total economic value of all products.

2.3. Results

Results are broken into two sections corresponding to the techno-economic and environmental analyses. All economic and environmental results across the two sections are coupled via the common process model which tracked materials and energy required for the production of rubber, resin, and bagasse. The economic and environmental results considered two scenarios: 1) the baseline scenario in which bagasse and resin are sold at predefined values and 2) the on-site heat and power scenario in which bagasse is combusted to generate heat and electricity.

2.3.1. Techno-Economic Analysis

The economic results of the baseline scenario are displayed in Figure 2.2. The figure includes the baseline minimum selling price of rubber at \$3.08 per kg along with corresponding costs and revenues. Total costs (\$4.91 per kg) are broken down to show major contributions from operations within agriculture (\$1.82 per kg of rubber) and rubber extraction (\$3.09 per kg of rubber). The contribution of agriculture at \$1.82 per kg of rubber corresponds to a cost of \$0.12 per kg of harvested guayule biomass. Within agriculture the largest overall cost was irrigation which required \$0.65 per kg of rubber. The next major contributors to agricultural cost were equipment with fuels and maintenance at \$0.52 per kg of rubber and plant fertilizers and herbicides at \$0.43 per kg of rubber. Other minor items such as insurance and taxes combine to make up the remaining agricultural cost of \$0.22 per kg. Within the rubber extraction, the largest individual cost contributors were capital/loan, solvents, and natural gas at \$0.91,

$0.63, and $0.40 per kg of rubber, respectively. The “other processing” category included costs from labor, maintenance, electricity, mineral oil, insurance, and water, all of which contributed less than $0.17 per kg of rubber individually, but sum to a total of $1.12 per kg of rubber. Transportation had a minimal impact of $0.02 per kg due to the relatively short transport distance of 44 km between the farm and the rubber extraction facility.

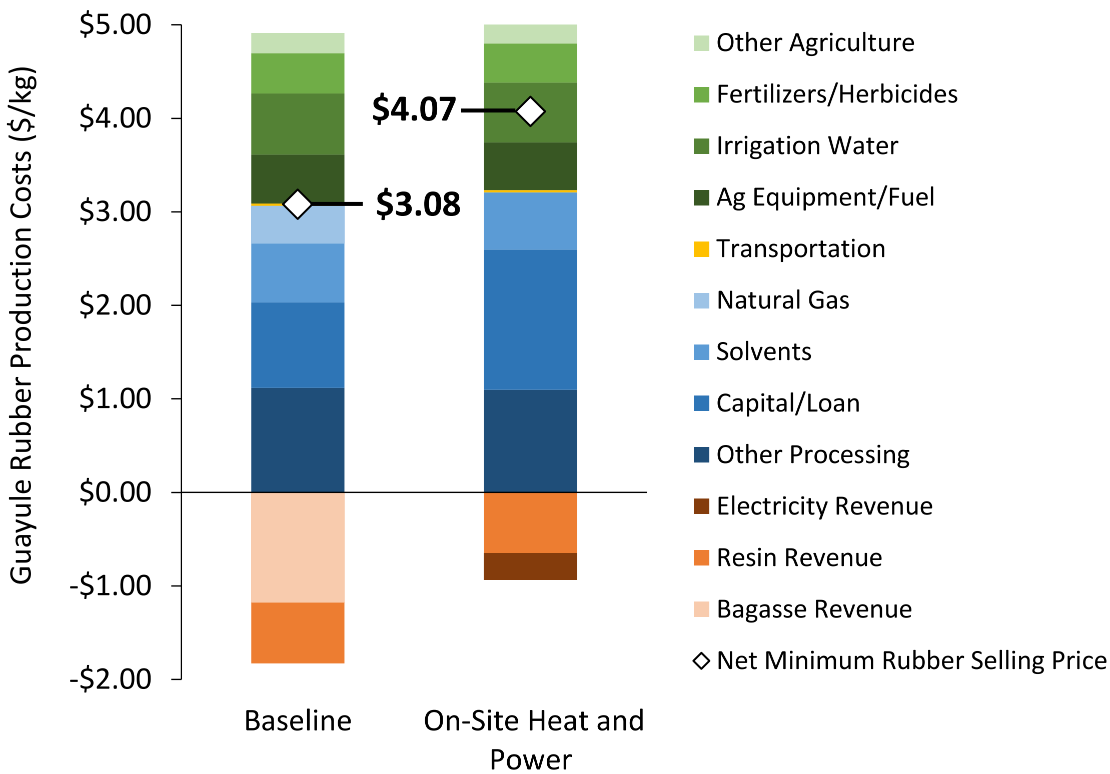

Figure 2.2. *Minimum guayule rubber selling price required for a net present value of zero over thirty years of production. Production costs are shown for agriculture (green), biomass transportation (yellow), and rubber extraction (blue). The baseline scenario includes co-product revenues (orange) of $1.00 per kg resin and $0.10 per kg bagasse. The on-site heat and power scenario includes co-product revenue of $1.00 per kg of resin and $0.05 per kWh of excess electricity.*

The alternative on-site heat and power scenario in which bagasse is combusted to replace electricity and natural gas consumption is also presented in Figure 2.2. In this scenario the minimum selling price was $4.07 per kg, an increase of 32% from the baseline scenario. This higher price was due to increased capital and loan costs from the purchase and installation of the combined boiler and turbine system. These results are clearly illustrated within Figure 2.2 in which the capital/loan costs of on-site heat and power are 164% that of the baseline scenario. In addition to this cost, the bagasse revenue of the baseline system was removed, increasing the rubber selling price further. The combined heat and power scenario did have the positive impact of removing the costs of natural gas and grid electricity, as well as generating revenue through the sale of excess electricity. However, the current low cost of natural gas and electricity lead to overall modest savings that did not offset the capital costs required for the heat and power system.

Results from the $\pm$20% sensitivity analysis performed on the baseline scenario are shown in Figure 2.3 with an expanded list shown in Figure A.2 of the appendix. Unsurprisingly, the rubber fraction of the guayule biomass had the largest impact of any variable on the minimum selling price as rubber mass is the functional unit of the TEA. The second highest impact variable was harvest yield. Although harvest yield had minimal impact on rubber extraction costs, it did have a large impact on overall agricultural costs. Other high impact parameters in the top ten are related to solvents, co-product revenue, and equipment costs. These variables align with the baseline results of Figure 2.2 in which solvents, capital costs, and co-product revenues were found to have large contributions to overall cost. The other remaining parameters in the top ten are harvest area and resin to rubber ratio, which had impacts on agricultural costs and expected resin revenue, respectively. Two notable parameters outside the top ten are natural gas and electricity costs. The lower sensitivity of these parameters agrees with the on-site heat and power scenario in Figure 2.2 where replacing natural gas and grid electricity with bagasse did not outweigh the added capital costs of a boiler and turbine system.

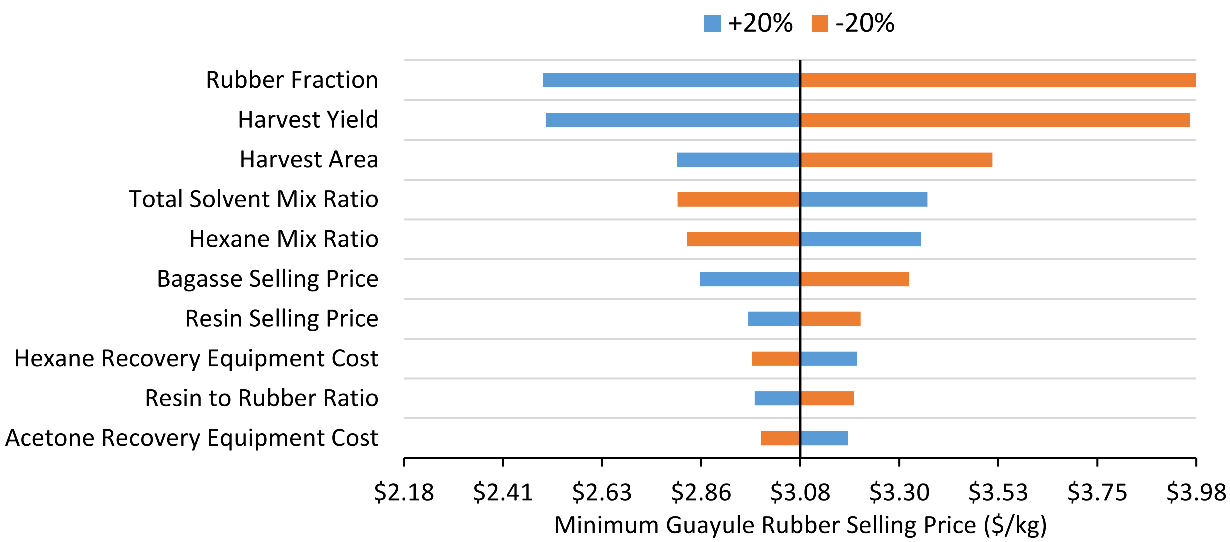

Figure 2.3. *Change in baseline scenario minimum rubber selling price due to varying individual input parameters by ±20%. The ten parameters with the largest impact are shown here, with an extended list of parameters shown in Figure A.2 of the appendix.*

2.3.2. Environmental Analysis

The environmental impacts of rubber, resin, and bagasse production are displayed in Table 2.4. These impacts include all burdens of the materials and energy consumed across agriculture, transportation, and rubber extraction. For example, the environmental impacts of natural gas used in solvent extraction included extraction from a well site, refining, distribution, and combustion at the rubber extraction facility. For the baseline scenario, the total impacts were distributed across rubber, bagasse, and resin using both mass and economic allocation. For the on-site heat and power scenario, a credit was given for excess electricity that was sold back to the grid, then the remaining impacts were allocated across rubber and resin based on mass and economic allocation.

Table 2.4. *TRACI 2.1 environmental impacts of guayule rubber, resin, and bagasse produced by one hectare of farm. Total impacts are aggregated across agriculture, transportation, and rubber extraction. Impacts in both scenarios are allocated by mass and economic methods. The on-site heat and power scenario includes a credit for excess electricity sold back to the grid.*

			Acidification (kg SO_2 eq)	**Ecotoxicity (CTUe)**	**Eutrophication (kg N eq)**	**Global Warming (kg CO_2-eq)**	**Human Health Carcinogenics (CTUh)**	**Human Health Non Carcinogenics (CTUh)**	**Ozone Depletion (kg CFC-11 eq)**	**Photochemical Ozone Formation (kg O3 eq)**	**Resource Depletion Fossil Fuels (MJ Surplus)**	**Respiratory Effects (PM 2.5 eq)**
Baseline	Impacts per hectare		6.37E+01	5.49E+04	6.36E+01	1.98E+04	6.52E-04	2.36E-03	2.10E-03	9.39E+02	3.99E+04	1.90E+01
	Mass Allocation (per hectare)	Rubber	4.73E+00	4.08E+03	4.73E+00	1.47E+03	4.84E-05	1.75E-04	1.56E-04	6.98E+01	2.97E+03	1.41E+00
		Bagasse	5.58E+01	4.82E+04	5.58E+01	1.74E+04	5.72E-04	2.07E-03	1.84E-03	8.23E+02	3.50E+04	1.66E+01
		Resin	3.08E+00	2.65E+03	3.08E+00	9.58E+02	3.15E-05	1.14E-04	1.01E-04	4.54E+01	1.93E+03	9.17E-01
	Economic Allocation (per hectare)	Rubber	3.91E+01	3.37E+04	3.91E+01	1.22E+04	4.00E-04	1.45E-03	1.29E-03	5.76E+02	2.45E+04	1.16E+01
		Bagasse	1.58E+01	1.37E+04	1.58E+01	4.93E+03	1.62E-04	5.86E-04	5.22E-04	2.34E+02	9.93E+03	4.72E+00
		Resin	8.72E+00	7.53E+03	8.72E+00	2.72E+03	8.93E-05	3.23E-04	2.88E-04	1.29E+02	5.47E+03	2.60E+00
On Site Heat and Power	Impacts per hectare		7.98E+01	2.93E+04	5.35E+01	7.77E+03	1.02E-02	1.96E-03	7.53E-03	1.81E+03	1.73E+04	3.09E+01
	Electricity Credit		1.25E+01	3.08E+04	4.10E+01	5.43E+03	4.30E-04	1.22E-03	4.10E-04	1.76E+02	4.41E+03	1.49E+01
	Impacts Minus Credit		6.72E+01	-1.49E+03	1.25E+01	2.35E+03	9.78E-03	7.36E-04	7.12E-03	1.63E+03	1.29E+04	1.60E+01
	Mass Allocation (per hectare)	Rubber	4.07E+01	-9.03E+02	7.58E+00	1.42E+03	5.93E-03	4.46E-04	4.32E-03	9.89E+02	7.84E+03	9.69E+00
		Resin	2.65E+01	-5.87E+02	4.93E+00	9.25E+02	3.85E-03	2.90E-04	2.80E-03	6.43E+02	5.10E+03	6.30E+00
	Economic Allocation (per hectare)	Rubber	5.80E+01	-1.28E+03	1.08E+01	2.03E+03	8.43E-03	6.35E-04	6.14E-03	1.41E+03	1.12E+04	1.38E+01
		Resin	9.25E+00	-2.05E+02	1.72E+00	3.23E+02	1.35E-03	1.01E-04	9.80E-04	2.25E+02	1.78E+03	2.20E+00

The relative contributions of different operations to total environmental impacts across all categories are shown in Figure 2.4. These contributions include agriculture (green), transportation (yellow), and rubber extraction (blue). Across the ten categories, agriculture ranged from 13% to 45% of the total environmental impact, while the rubber extraction process made up between 52% and 87% of the overall impact. Similar to techno-economic results, transportation had an overall impact less than 3% across all categories due to minimal transportation distances between the farm and the rubber extraction facility. Within agriculture, fertilizer application had the largest impact across the majority of categories, followed by irrigation which uses a large amount of electricity for water pumping. Within rubber extraction, the largest overall impacts came from solvent mixing, resin extraction, and solvent recovery. The large impact of solvent mixing was due to high solvent flow rates coupled with the upstream environmental impacts of producing solvents. The impact of resin extraction and solvent recovery was due to large quantities of natural gas used to distill and purify the components of the resin-solvent mixture. This distillation enables the sale of a pure resin co-product and the reuse of solvents within the extraction process, avoiding the need for additional make-up solvent which would increase environmental burden.

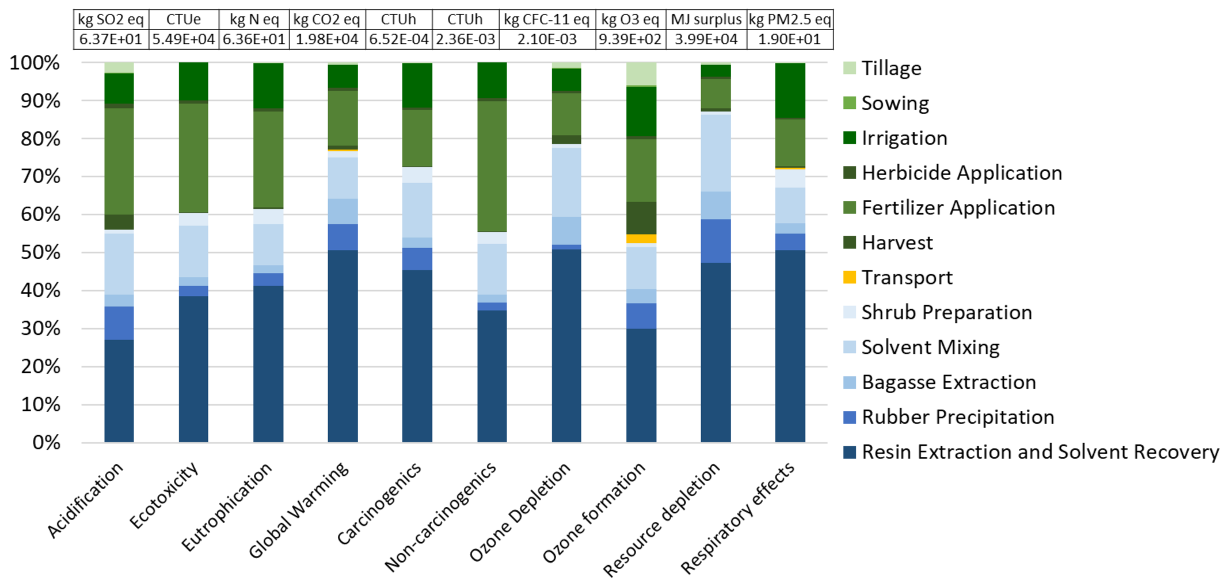

Figure 2.4. *The relative contributions of TRACI 2.1 environmental impacts for the baseline scenario broken out by agriculture (green), transportation (yellow), and rubber extraction (blue). Total impact per hectare are displayed across the top of the figure.*

2.4. Discussion

The results of Sections 3.1 and 3.2 lead to four major points of discussion: 1) the current estimate of a minimum guayule selling price is on the high end of hevea rubber prices, but it can be reduced via the three key parameters of biomass yield, rubber content, and resin co-product value, 2) the value and fate of co-products, most notably the resin, represents a large source of uncertainty warranting further research and development, 3) current global warming emission results are similar to hevea rubber production, but the end use of bagasse and LCA allocation methods have a large impact on the environmental results, and

4) results of this work can be compared with previous analysis for validation, but the results of this study move beyond previous work and advance our understanding of guayule rubber production and future opportunities.

2.4.1. Economic Comparison to Hevea Rubber

The success of guayule rubber in the southwest United States is largely dependent upon the economics of production. A direct comparison of the economic results from this study to the current market values for two existing types of hevea rubber is presented in Figure 2.5. In the figure, the baseline minimum selling price of $3.08 per kg of guayule rubber found in this study is within the bounds of hevea rubber market values over the past ten years[42,43]. However, it lands in the upper 25th percentile of values, meaning at this price point it is typically more expensive than hevea rubber. Improving key performance parameters could reduce the price of guayule rubber to be within the inner 50th percentile of market values, making it more competitive with hevea rubber. As demonstrated in the sensitivity analysis (Figure 2.3), two parameters that have a large impact on selling price are the agricultural harvest yields and the rubber content of guayule biomass. Improving these parameters, along with the resin co-product value through further research and development could reduce the minimum required selling price of guayule rubber. For example, in Figure 2.5, the agricultural harvest yield was increased from 30 to 32 metric tons per hectare, the rubber content was increased from 7.5% to 8.5%, and the resin value was increased from $1.00 to $2.00 per kilogram of resin. Solving the model with these new input values resulted in a minimum selling price of $1.91 per kg of guayule rubber, a 38% decrease from the baseline value of $3.08 per kg of rubber. The proposed increases represent optimistic but realistic potential future performance. This new value falls within the inner 50th percentile of existing market prices, making guayule more competitive with hevea.

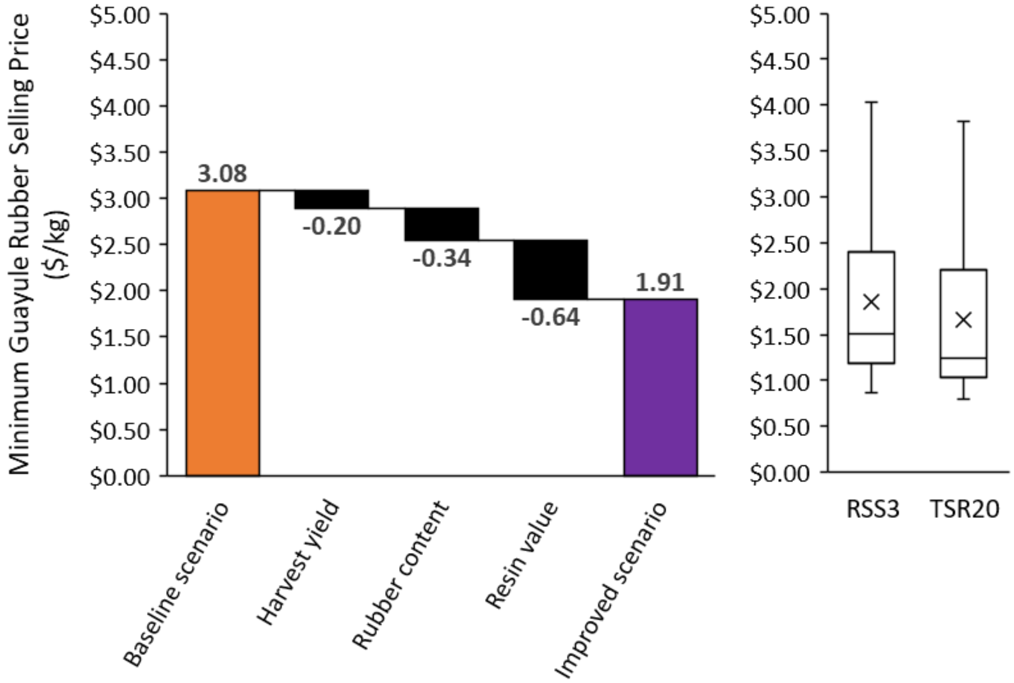

***Figure 2.5**. (Left) Change in minimum selling price from baseline scenario at $3.08 per kg to improved scenario at $1.91 per kg. The improved scenario includes increasing harvest yield to 32 metric tons per hectare, increasing rubber content to 8.5%, and increasing resin value to $2.00 per kg. Black bars represent the individual impact of each variable, while the purple bar represents the cumulative impact of all three variables. (Right) Market values for Ribbed Smoked Sheets (RSS3) and Technically Specified Rubber (TSR20) on the Singapore Exchange. Market price distributions are based on monthly prices from December of 2009 through November of 2019 with the X symbol marking the mean value over that timeframe[42,43].*

2.4.2. The Impact of Uncertainty and Co-products

Resin and bagasse co-products will play an important role in the economic viability of guayule rubber[44,45]. In order to highlight the impact of co-products, the variation of minimum rubber selling price as a function of resin and bagasse value is presented in Figure 2.6. When bagasse is sold at the baseline value of $0.10 per kg and resin is varied from $0-$3.00 per kg, the minimum selling price of rubber ranges from $3.72 per kg down to $1.82 per kg. The large impact of resin value on rubber selling price is largely because rubber and resin make up similar quantities of the guayule biomass. Therefore, these two products have similar impacts on revenue and corresponding economic viability. This reflects the importance of the resin, which remains the least certain value in this TEA. Reducing uncertainty through future resin application research is critical to the success of guayule as a natural rubber feedstock.

The relatively well-established pathways from lignocellulosic biomass to biofuels makes the value of the bagasse more defined than the resin. For example, the previous TEA of guayule bagasse pyrolysis places the value of bagasse at $0.052 per kg[13] and the study of guayule rubber production in the Mediterranean puts bagasse at $0.11 per kg[18]. Given these data points as well as earlier estimates[19], it is unlikely guayule bagasse will greatly exceed a value of the $0.15 per kg, used in this work to represent a high end estimate. As shown in Figure 2.6, increasing the bagasse value from $0.10 to $0.15 per kg reduces the minimum selling price of rubber by $0.59 per kg. The alternative to selling guayule bagasse is on-site combustion to produce electricity and heat. Combusting the bagasse in this scenario is less complex than the logistics of biofuel production. However, the relatively low costs of natural gas and electricity, as well as the increase in capital cost leads to the overall cost increase shown in Figure 2.6.

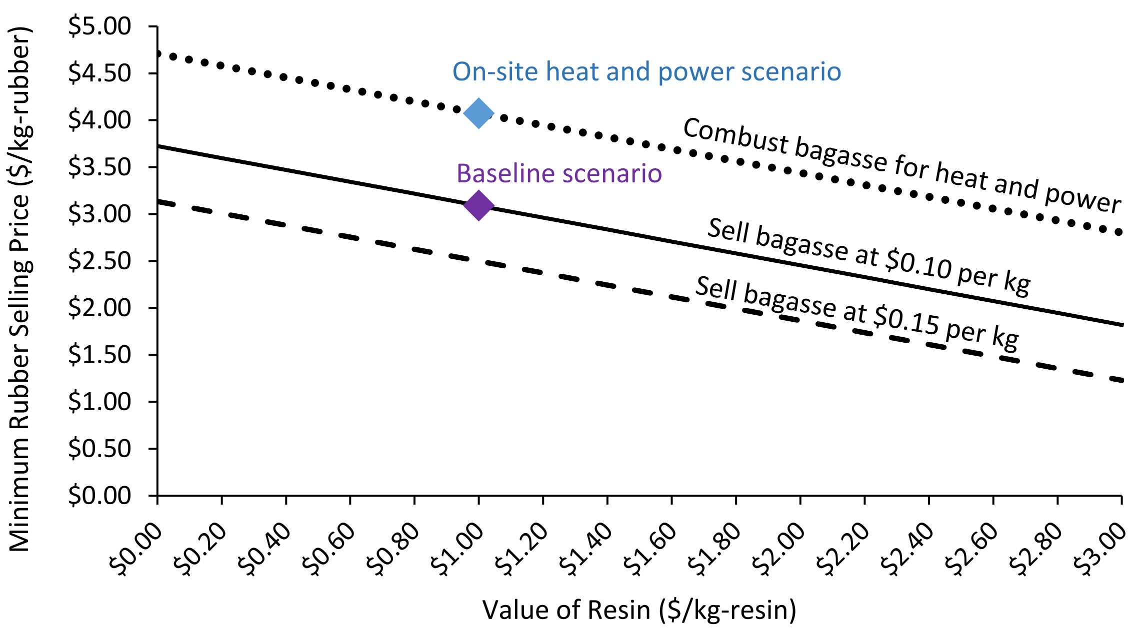

Figure 2.6. *Variation of minimum rubber selling price as a function of the value of resin. Diagonal lines represent different bagasse scenarios, one where bagasse is combusted for on-site heat and power and two others where bagasse is sold at values of $0.10 per kg (baseline) and $0.15 per kg. Diamond markers represent the baseline (purple) and on-site heat and power (blue) results of Section 3.1.*

2.4.3. The Impact of Scope, Allocation, and On-Site Heat and Power on Global Warming Results

There are a range of economic considerations that can alter the costs and benefits of guayule production. Similarly, there are a broad range of considerations that can shape the environmental impacts of guayule based products. Critical considerations included in this analysis were the selection of an allocation method, and the use of bagasse for heat and power. The effect of these considerations on global warming are presented in Table 2.5 (A). In the baseline scenario, the global warming of guayule rubber varies from 0.77 to 6.48 kg CO_2-eq per kg rubber depending upon allocation method. The low end of this range is the result of the large mass of bagasse which is allocated the majority of environmental burden in the mass allocation method. This allocation of burden to bagasse is beneficial from the perspective of rubber production. However, the large bagasse burden must be accounted for in downstream production of products such as biofuels, which is likely to make those products environmentally unattractive. The alternative perspective of economic allocation balances out the large mass of bagasse with its relatively low economic value, which in turn increases the impact of rubber to 6.48 kg CO_2-eq per kg rubber.

The large difference between mass and economic allocation results in the baseline scenario makes it difficult to conclude the true environmental impact of guayule rubber. Following standard LCA practice by increasing the system boundary to include the end use of rubber, resin, and bagasse would alleviate the need for allocation. However, doing so would require defining the end use of all products, which at this point is highly uncertain. Considering this limitation, both allocation results are presented, with market allocation deemed the preferred option as it is less biased by the large mass ratio of bagasse to resin and rubber. The on-site heat and power scenario shows far less variability between allocation methods as the rubber and resin products have similar masses. Therefore, the choice between allocation methods for on-site heat and power is not critical to the overall outcome. Table 2.5 (B) also includes global warming estimates for synthetic Styrene Butadiene Rubber (SBR) and hevea rubber, which are explained in greater detail in the appendix.

Table 2.5. *(A) Global warming of guayule rubber production for baseline and on-site heat and power scenarios allocated by mass and economics. (B) Estimated global warming values for domestic synthetic styrene butadiene rubber (SBR)*[25,39,46] *and ribbed smoked sheets (RSS3) produced in Thailand*[47].

A. Global Warming of Guayule Rubber Production kg CO_2-eq / kg guayule rubber		
	Baseline	On Site Heat and Power
Mass allocation	0.77	0.74
Economic Allocation	6.48	1.05

B. Global Warming of Standard Rubber Production kg CO_2-eq / kg rubber	
Synthetic Rubber	3.05
Hevea Rubber	0.91

It is important to note that consideration of direct field emissions from agricultural practices and alternative (drip or sprinkler) irrigation practices were excluded from this analysis. Field emissions were not included as the data does not exist, meaning current results may underestimate agricultural impacts related to water and air quality. These emissions are expected to be included in future modeling efforts as data becomes available. Conversely, there is already a large amount of data relating to the impacts of irrigation, which can present widely different environmental results based on the type and amount of water applied[26]. Given the already broad scope of this integrated analysis, a single irrigation method (surface flood) was selected as it reflects the least complex and most common method used for guayule cultivation in the United States.

2.4.4. Comparison to Existing Literature

The lack of previous research on guayule economics makes comparing the results of this study to previous work challenging. However, the previous analysis of a guayule production chain in the Mediterranean does serve as a reference point[18]. In one scenario of that analysis, crude rubber, latex, resin, and bagasse were produced, with inputs of 5.9%, 2.2%, 9.0%, and 75% of biomass, respectively. The analysis resulted in selling prices of $2.38, $2.73, $2.34, $0.11 per kg for crude rubber, latex, resin, and bagasse, when converted to U.S. dollars using 2019 exchange rates. Although, the production of latex and crude rubber differs from the rubber extraction in this analysis, these results can be roughly compared with the improved scenario considered in Figure 2.5, which uses similar input parameters and results in a guayule rubber selling price of \$1.91 per kg. The comparison does provide some initial validation of overall model results, but does not confirm many specific assumptions. Significant differences in the foundational biomass production and extraction process makes further exploration of differences unrealistic.

Within the environmental analysis, the total global warming results of the baseline scenario (10.3 kg CO_2-eq per kg of rubber) compare favorably with results from the previous LCA (13.8 kg CO_2-eq per kg of rubber produced)[25]. In addition to the baseline scenario, previous studies have also evaluated the generation of electricity by combusting bagasse. In general, these studies have demonstrated a significant reduction in global warming emissions as combustion of biomass typically results in lower emissions than electricity sourced from the grid[25,27]. While the current on-site heat and power scenario also finds a reduction of global warming emissions, it takes the analysis a step further to include the increase in overall cost resulting from bagasse combustion in an expensive boiler and turbine system. As a result, the on-site heat and power scenario in this integrated analysis has highlighted the important economic and environmental tradeoffs that can occur during process development. As development of guayule continues, these tradeoffs should be evaluated to better understand the impact of future decisions and optimize a path toward reducing both costs and environmental impacts.

2.5. Conclusions

The evaluation of guayule with standard TEA and LCA methods provides valuable insight for future development aimed at decreasing cost and environmental impact. The baseline minimum selling price for guayule rubber production is \$3.08 per kg. The environmental impact varies across categories, with a baseline global warming potential ranging from 0.77 – 6.48 kgCO_2-eq per kg rubber depending upon which allocation method is selected. The largest contributor to cost and environmental impacts is rubber extraction, which relies upon energy intensive solvent extraction. Coproducts play a critical role, with bagasse and resin offsetting a significant amount of production cost. However, the value of these coproducts remains uncertain and varying their price effects results. Furthermore, opting to use the bagasse to generate on-site heat and power increases cost but reduces environmental impacts, resulting in economic and environmental trade-offs.

The economic and environmental trade-offs of using bagasse for on-site heat and power are hard to compare as the metrics of TEA and LCA are disconnected. There is no direct way to relate $ per kg of guayule rubber to kg CO_2-eq per kg of guayule rubber. As a result, it is left up to the analyst or other stakeholders to subjectively decide whether decreased cost or environmental impact is more desirable. Furthermore, the LCA greenhouse gas emissions presented in the evaluation of guayule represent a temporally unresolved result, in which emissions are averaged over the full lifetime of the bioprocessing facility. Unlike TEA which incorporates a time-value of money, standard LCA methods do not consider the potential for greenhouse gas emissions to have a changing effect on the climate or society over time. As a result, the comparison between TEA and LCA metrics is unequal and does not convey the true trade-offs associated with a technology option such as on-site heat and power. Improving upon these limitations in TEA and LCA is addressed in the following chapter. The chapter is focused on developing new TEA and LCA methods based on large-scale climate science, macroeconomics, and temporal resolution. These metrics are then applied to multiple technologies to identify areas where this new approach can add value and where it is still limited.

CHAPTER 3: INTEGRATED TEA AND LCA WITH TEMPORAL RESOLUTION[b]

3.1. Background

Overcoming the limitations of standard TEA and LCA requires new methods that address the disconnect between metrics of performance and the lack of temporal resolution in LCA. While both of these topics have been addressed before, the lack of temporal resolution has been a particular point of contention within the LCA community and has been highlighted as a major limitation in previous reviews[48–51]. When specifically considering greenhouse gases, the lack of temporal limitation stems from the use of global warming potential (GWP). GWP is the ratio of cumulative radiative forcing (CRF) of a greenhouse gas emission to the CRF of a CO_2 emission. GWP allows us to compare the CRF of different greenhouse gases and relate emissions to an equivalent amount of CO_2. Despite being the current standard for comparing greenhouse gases, GWP is acknowledged by the International Panel on Climate Change (IPCC) and others to be a simplified metric that does not account for a range of dynamic temporal factors[52–55].

One specific point of debate has been the use of a constant GWP analytical time frame (often 100 years) within LCA. A number of researchers have raised issues with this practice, noting that it ignores the actual timing of emissions[56–58]. They highlight that an emission released early in the LCA time frame will be in the atmosphere for a longer period of time than an emission released in a later year. As a result, the earlier emission will generate more CRF than the later emission. The proposed solution for this discrepancy is the implementation of a LCA time horizon. The time horizon is a cutoff year after which the CRF of an emission is no longer considered. To demonstrate the concept, consider a hypothetical time horizon of the year 2100. If an emission is released in the year 2020, the CRF of this emission will be analyzed over 80 years before reaching the time horizon. If an equivalent emission is released in the year

[b] Portions of this chapter have been published as a peer-reviewed journal article: Sproul, E., Barlow, J. & Quinn, J. C. Time Value of Greenhouse Gas Emissions in Life Cycle Assessment and Techno-Economic Analysis. Environmental Science & Technology 53, 6073–6080 (2019).

2050, this emission will be analyzed for only 50 years and result in lower CRF. The impact of implementing a time horizon has been explored by a variety of researchers.

O'Hare et al.[56] were some of the first to implement the time horizon approach by developing the Fuel Warming Potential (FWP). The FWP compares the CRF between biofuel emissions and petroleum fuel emissions up to a fixed time horizon. In addition, O'Hare et al. also extended modeling to translate CRF into economic damages that could be discounted to a present value. This work showed that biofuels have an increased impact when accounting for time, largely due to the heavy burden of land use changes occurring during early stages of biofuel production. Kendall et al. [57] also developed a Time Correction Factor (TCF) for adjusting amortized emissions to account for actual emissions timing. Similar to the FWP, the TCF utilized CRF up to a time horizon as the driving metric for impact. In this case, Kendall et al. showed that correcting amortized emissions to consider time increased the impacts of corn-ethanol.

Building upon these efforts, Levasseur et al.[58] developed a more generalized form of dynamic LCA. Like previous efforts, this dynamic LCA utilized CRF to gauge impact up to a time horizon. Unlike previous efforts, this method was not limited to the specific cases of fuels or amortized emissions. Since this introduction of dynamic LCA, an iterative development of methods has continued[59–66]. Throughout this development, the underlying methods have remained much the same with efforts largely focused on adapting and applying a time horizon to specific scenarios where temporal impacts can play a significant role. This includes assessments of advanced vehicles, buildings, biogenic carbon and temporary storage, gasification of crop residues, cellulosic biofuels, and photovoltaics.

The methods presented across these analyses show specific implications of accounting for emissions timing within LCA. However, these methods are often limited to only correcting the analytical time frame and do not account for other dynamic factors. One such factor is the ongoing increase in atmospheric greenhouse gas concentrations. This increase will slow down the rate at which future emissions are removed from the atmosphere and decrease the radiative efficiency of those emissions[67]. While there is potential for these two factors to counteract one another[68], current LCA practice completely ignores these effects. Recognizing the exclusion of dynamic climate factors, Farquharson et al.[69] used the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) to compare life cycle greenhouse gas emissions of natural gas and coal power generation. In this dynamic analysis, the results of MAGICC are compared across several climate metrics including GWP, Global Temperature Change, and CRF. Results highlight that each metric provides different results and can be useful for decision making with a given set of societal values or targets.

The work by Farquharson et al.[69] addresses a broad range of dynamic climate variables through the use of MAGICC. However, downstream of these climate impacts lie other dynamic factors embedded in socio-economic systems such as economic productivity and future technology deployment. These variables will impact how climate change manifests into economic damage. Many integrated assessment models (IAMs) used to model climate change and related economic impacts account for these sort of dynamic variables. Often, the models utilize a nonlinear trend in which economic damage increases exponentially with the rise of global temperature[70]. This increase means that radiative forcing in future years will have a significantly higher monetized impact than radiative forcing in the present. Although this topic is under debate, using metrics such as CRF, GWP, or temperature change in LCA totally excludes these considerations[71].

While many LCA researchers recognize the potential for nonlinear socio-economic impacts, there have been few attempts to account for them in LCA. A rare example of such an attempt is Delucchi's[72,73] development of the Lifecycle Emissions Model (LEM). Within the LEM, emissions are modeled with increasing background atmospheric greenhouse gas concentrations. Then, using a climate sensitivity factor and nonlinear damage function, an emission's radiative forcing is translated into temperature change and economic damage. By comparing the present value of damage from a greenhouse gas emission to an equivalent CO_2 emission, the model can yield Carbon Equivalency Factors (CEFs). This comparison represents a significant advancement compared to previous methods. Yet, the CEFs are strictly a comparison of economic damage from a greenhouse gas emission and CO_2 emission that are released in the same year. The CEFs do not compare the damage of greenhouse gas emissions and CO_2 emissions that are released in different years. Therefore, the CEFs do not provide a comparison of changing impacts across different years.

Previous work from individuals such as Delucchi, Farquharson, Lavasseur, and Kendall demonstrates the need for temporal considerations in LCA. Yet, none of the approaches presented fully resolve the disconnects that restrict our ability to compare greenhouse gas emissions of LCA and economic considerations of TEA. This phase of research addresses these issues through a new form of analysis that builds upon previous efforts, but goes several steps beyond existing methods to integrate dynamic climate models, socio-economic impacts, and time resolved LCA and TEA. The novel outcomes of this research phase are 1) a new LCA weighting method that includes temporally resolved atmospheric greenhouse gas concentrations and non-linear economic damages to society, 2) a new TEA method that includes temporally resolved greenhouse gas emissions and social costs of greenhouse gases, and 3) application of both new methods to case studies of electricity generation and guayule rubber production.

3.2. Methods

3.2.1. Social Costs of Greenhouse Gases

The methods in this phase of research seek to address the shortcomings of current dynamic LCA by following Delucchi's[72,73] general approach, and further advancing the methods to compare the monetized impact of greenhouse gas emissions in the future with monetized impacts of CO_2 emissions in the present. The monetized impacts considered in this research are the social costs of greenhouse gases developed by the Interagency Working Group (IWG) on Social Cost of Greenhouse Gases[70,74,75] . These costs are derived using IAMs that model climate and economic systems on a global scale. These systems include consideration for the carbon cycle, climate sensitivity, future technology deployment, economic productivity, and a variety of other variables. To develop the social cost of greenhouse gases, the IAMs are run under two different scenarios. The first scenario tracks the global gross domestic product (GDP) for a specific future global emissions pathway up to the year 2300. The second scenario runs the same pathway, but also includes one extra pulse of greenhouse gas emitted in a specific year. The difference in global GDP between these two scenarios represents the monetized social damage due to a marginal greenhouse gas emission.

This procedure is repeated across three separate IAMs (PAGE, DICE, and FUND) for a range of five potential socio-economic emissions scenarios. The values of each model and scenario are averaged to arrive at a single damage value. This damage is then discounted back to a present value using an economic discount rate. The use of a specific discount rate has been a subject of much debate. As a result, current estimates for the social cost of greenhouse gases include results from a range of low (2.5%), middle (3%), and high (5%) economic discount rates. Additionally, a fourth cost has been developed to represent higher than expected damages. In this scenario, low probability high impact damages outside the 95th percentile are discounted back at a rate of 3%, generating the low probability high impact (3%-95th) social cost. Table 3.1 displays the social costs of greenhouses gases for the four discounting scenarios. The table shows values on a five-year incremental basis for 2020-2050. A full list of yearly values is presented in Table B.3 of the appendix.

Table 3.1. *Social Costs of Greenhouse Gases: Social cost of one metric ton of greenhouse gas (2020 US dollars) based on 2.5%, 3%, 5%, and 3%-95th percentile IAM discount rates*[70,74,75].

Year of Emission	Social Cost of CO_2				Social Cost of CH_4				Social Cost of N_2O			
	5%	3%	2.5%	3%-95th	5%	3%	2.5%	3%-95th	5%	3%	2.5%	3%-95th
2020	23	62	85	181	1,018	1,762	2,206	4,699	8,863	22,028	30,327	57,273
2025	26	68	94	203	1,226	2,056	2,481	5,434	10,371	24,965	33,084	64,615
2030	30	73	101	223	1,433	2,350	2,757	6,168	11,880	27,902	37,220	71,958
2035	34	81	108	247	1,697	2,643	3,171	7,196	13,954	30,839	39,977	80,769
2040	40	88	116	269	1,886	2,937	3,584	8,077	15,839	33,776	44,112	88,112
2045	43	94	123	289	2,263	3,378	3,860	8,958	17,914	36,713	46,869	96,923
2050	49	101	131	311	2,451	3,671	4,273	9,839	20,742	39,650	51,005	105,734

As shown in Table 3.1, social costs increase for greenhouse gases emitted in future years. This increase is a direct result of exponential damage functions representing scenarios in which global systems become more stressed over time[74]. Using the increasing SC-CO_2, SC-CH_4, and SC-N_2O values, a dynamic global warming impact (DGWI) is derived to compare the monetized impacts of greenhouse gas emissions relative to today's environmental and economic conditions. Analogous to the present value of money commonly discussed in economics, this approach weights the value of emissions based on their monetized impact at a given time.

3.2.2. Deriving the Dynamic Global Warming Potential

The Dynamic Global Warming Impact (DGWI) is derived to compare of the monetized impact of a marginal emission released in a future year, to the monetized impact of a marginal CO_2 emission released in the present year. This comparison represents the change in monetized impact of emissions due to dynamic greenhouse gas concentrations and socio-economic damage functions. As shown in Equation 3.1, the DGWI is a ratio of the social cost of a particular greenhouse gas (GHG) in the future year (i), to the social cost of CO_2 in the present year. A full list of terms used within equations of this chapter is located in the appendix.

$$Dynamic\ Global\ Warming\ Impact_{GHG,i} = \frac{Social\ Cost_{\ GHG,i}}{Social\ Cost_{\ CO_2,2020}} \tag{3.1}$$

DGWI values were generated for CO_2, CH_4, and N_2O using the SC-CO_2, SC-CH_4, and SC-N_2O, respectively. The DGWI compares the monetized damage of one gas to another and includes consideration for when that gas is emitted. Applying the DGWI converts individual gases (CO_2, CH_4, and N_2O) to a CO_2 equivalent, similar to the GWP. DGWI values were generated across the full range of discount factors used to develop the social costs of greenhouse gases. Generating these values required applying Equation 3.1 to the four separate discount rates in each year. In each calculation, the social cost based on a specific discount rate was compared to the social cost of CO_2 in the present based on the same discount rate. While the impacts of all four discount rates are included in this research, the 3% discount rate is the central value of social cost estimates[74] in the literature, and is thus considered the baseline in this analysis.

3.2.3. Developing Temporally Resolved Life Cycle Assessment Data

In order to apply the DGWI and demonstrate the monetized impact of emissions, temporally resolved LCA emissions were developed for conventional electricity-generation technologies and guayule rubber production. Electricity generation technologies included coal, natural gas, nuclear, solar photovoltaic (PV), concentrating solar power (CSP), and wind. Additional temporally resolved LCA emissions for post-combustion carbon capture and sequestration (CCS) were defined and applied to both coal and natural gas. To generate temporal emissions for electricity generation, two primary phases were defined over the lifetime of a technology. The first was construction, which is assumed to occur in the first year of the lifetime. The second was operation, which occurs over the entire 30-year span of the lifetime. Emissions data was obtained for construction and operation from existing literature[63,76–84]. Results of this data collection effort are summarized in Table 3.2. For the purposes of this research, CH_4 and N_2O operational emissions are considered negligible for PV, CSP, nuclear, and wind due to their expected impact being less than 6 gCO_2-eq per kWh in all scenarios. This decision aligns with findings from a number of previous studies[82–84]. Details of references used to derive emissions and an example emission profile for coal with CCS (Figure B.2) are presented in the appendix.

Table 3.2. *Life Cycle Emissions: Construction and operational greenhouse gas emissions used to generate temporally resolved LCA results for energy generation technologies*[63,76–84].

Technology	Construction Emissions (g/kWh)			Operational Emissions (g/kWh-year)		
	CO_2	CH_4	N_2O	CO_2	CH_4*	N_2O*
Coal	41	0.04	0.001	936	3	0.0001
Coal CCS (90%)	56	0.06	0.002	152	5	0.0001
Natural Gas	23	0.03	0.001	384	3.87	0.0001
Natural Gas CCS (90%)	30	0.04	0.001	69	4.53	0.0001
PV	949	5.58	0.015	0.1	-	-
CSP	606	1.53	0.175	17	-	-
Nuclear	89	0.18	0.001	4	-	-
Wind	97	0.32	0.008	0.1	-	-

*Operational CH_4 and N_2O emissions considered negligible for low emissions technologies.

For guayule rubber production, temporally resolved emissions included agriculture, transportation, and rubber extraction. Since guayule is perennial crop, the first two years of cultivation (establishment and harvest) occur without any rubber production. In these initial years, the emissions associated with guayule are limited to agricultural emissions resulting from activities such as diesel combustion within agricultural equipment and electricity required for pumping irrigation water. At the end of year two, the initial crop can be harvested and transported to the rubber extraction facility to begin production. From year three through the end of the rubber extraction facility's 30-year lifetime agriculture, transportation, and rubber extraction are assumed to occur simultaneously such that rubber extraction facility can maintain constant steady-state production. In an effort to maintain consistency with the guayule analysis of the previous chapter, embedded emissions of the rubber extraction facility were omitted due to their minimal impact over the lifetime of the facility. As a result, the analysis of guayule presents a contrast to the analysis of electricity generation, where embedded emissions are included in the construction phase. The emissions associated with guayule production are summarized in Table 3.3. Within the table transportation emissions are included within the rubber extraction category.

Table 3.3. *Life Cycle Emissions: Agriculture and rubber extraction greenhouse gas emissions used to generate temporally resolved LCA results for guayule rubber production.*

Emissions (kg per ha)	**CO_2**	**CH_4**	**N_2O**
Establish	1332	2.2	2.2
Grow	1355	3.4	2.2
Harvest	1624	3.6	2.2
Rubber Extraction	13917	53.6	0.1

A present value of emissions for electricity and guayule rubber, represented by a mass of CO_2-eq, was generated for each year based upon the temporally resolved LCA emissions and DGWI values. As shown in Equation 3.2, this present value represents emissions that are weighted by their impacts based on when they are released relative to the impact of CO_2 in the present. To compare with traditional LCA methods, a mean present value of emissions over all years (n) of a technology's lifetime was also generated as displayed in Equation 3.3. This equation yields a single emissions value, but unlike standard methodology this value includes temporally resolved impacts quantified in gCO_2-eq per kWh.

$$Present\ Value_{GHG,i} = Emissions_{GHG,i}\ \times DGWI_{GHG,i} \tag{3.2}$$

$$Mean\ Present\ Value = \frac{\sum_{i=1}^{n} Present\ Value_{CO_{2},i} + Present\ Value_{CH_{4},i} + Present\ Value_{N_{2}O_{i}}}{\sum_{i=1}^{n} Electricity\ Generated_{i}} \tag{3.3}$$

3.2.4. Incorporating the Social Cost of Carbon in TEA

In addition to the alternative LCA method, a separate combined LCA/TEA approach was also considered. This combined approach included integration of dynamic SC-CO_2, SC-CH_4, and SC-N_2O values with temporally resolved LCA to generate a yearly cost of emissions. Integrating these costs into TEA demonstrated the impact of greenhouse gas emissions on the levelized cost of electricity (LCOE) and minimum selling price of guayule rubber. The first step in this integration was generating a discounted cash-flow rate of return TEA for each of the technologies. The National Renewable Energy Laboratory's (NREL) Annual Technology Baseline was used to define the capital and operational costs as well as other economic parameters for each electricity generation technology[85]. The Guayule TEA was based upon the work presented in Chapter 2. Details of the specific costs and parameters for each model are located in Table B.1, Table B.2, and Chapter 2.

With the conventional TEA cash flows defined for electricity and guayule rubber production, an additional yearly cost was added based on the greenhouse gas emissions and the corresponding social cost. As displayed in Equation 3.4, this cost was generated by taking the emissions occurring in a given year multiplying them by the corresponding social cost. As with the DGWI, a range of SC-CO_2, SC-CH_4, and SC-N_2O values were considered based on the 2.5%, 3%, 3%-95th percentile, and 5% economic discount rates. To remain consistent with an analysis conducted in the year 2020, the 2.5%, 3%, and 5%

economic discount rates were used to shift the social cost values originally given in 2007 US dollars to 2020 US dollars [74,75].

$$Emissions\ Based\ Operational\ Cost_{GHG,i} = Emissions_{GHG,i} \times Social\ Cost_{GHG,i} \qquad \textbf{\textit{(3.4)}}$$

After defining all costs associated with a technology the TEAs were solved for the LCOE and minimum selling price of guayule rubber. These results represent the minimum selling price of electricity or rubber to offset production costs (including emissions damages) and at a defined internal rate of return. By incorporating emission costs directly into the LCOE and minimum selling price, the new method merges temporally resolved LCA with TEA to account for the dynamic impacts of emissions over time. It is important to note that this dynamic TEA represents an analysis of private-costs. As a result, the analysis assumes that the external social costs of greenhouse gases will be translated into private costs through a mechanism such as a carbon tax.

3.3. Results

3.3.1. Expanding Life Cycle Assessment to Include Temporal Impacts

Incorporating temporal impacts into LCA is based on the development of DGWI values combined with time resolved LCA. Table 3.4 summarizes DGWI every five years from 2020-2050. A full list of annual values is located in Table B.3 of the appendix. In an effort to capture the uncertainty associated with future impacts, the social costs of each gas include the four different IAM discount rates. Reviewing Table 3.4 it is clear that all DGWI values increase over time, demonstrating that future emissions will have greater impact. Looking specifically at CO_2, the DGWI values in the year 2050 range from a low of 1.53 to a high of 2.17, corresponding to the 2.5% and 5% SC-CO_2 scenarios, respectively. The baseline scenario resulting from the 3% SC-CO_2 discount rate shows growth to a DGWI of 1.64 over the 30-year period. This foundationally means a CO_2 emission occurring in 2050 would have a 64% higher monetized impact than the same emission occurring in the year 2020.

Similar increases in future years occur across CH_4 and N_2O DGWI values with each gas demonstrating its own specific impact based on its role in future climate scenarios. Looking at the initial analysis year of 2020, the range of CH_4 and N_2O DGWI values are significantly different than current GWP values. This difference is the result of comparing monetized impact instead of CRF. For example, Table 3.4 shows that the monetized impact of N_2O is expected to be 317-392 times greater than CO_2. Meanwhile, IPCC's 100-year GWP method yields the smaller ratio of 265[52]. Comparing the two metrics demonstrates the importance of going beyond CRF to include monetized impacts, especially when assessing the contributions of N_2O and CH_4 in an analysis.

Table 3.4. *Dynamic Global Warming Impact: comparison of social cost of greenhouse gases in future years to the year 2020 for five year increments from 2020-2050.*

Year of	DGWI of CO_2				DGWI of CH_4				DGWI of N_2O			
Emission	**5%**	**3%**	**2.50%**	**3%-95th**	**5%**	**3%**	**2.50%**	**3%-95th**	**5%**	**3%**	**2.50%**	**3%-95th**
2020	1.00	1.00	1.00	1.00	45	29	26	26	392	357	355	317
2025	1.17	1.10	1.10	1.12	54	33	29	30	458	405	387	358
2030	1.33	1.19	1.18	1.24	63	38	32	34	525	452	435	398
2035	1.50	1.31	1.26	1.37	75	43	37	40	617	500	468	447
2040	1.75	1.43	1.35	1.49	83	48	42	45	700	548	516	488
2045	1.92	1.52	1.44	1.60	100	55	45	50	792	595	548	537
2050	2.17	1.64	1.53	1.72	108	60	50	54	917	643	597	585

Applying the DGWI to temporally resolved LCA of electricity generation technologies yielded the mean present value of emissions shown in Figure 3.1. The figure also includes standard LCA results for comparison. These standard results are based on IPCC's 100 year GWP values of 28 gCO_2-eq and 265 gCO_2-eq for CH_4 and N_2O, respectively[52]. Comparing the results of standard LCA to the new DGWI method shows an increase across all technologies, except PV where the 2.5% and 3%-95th scenarios result in slightly lower values than standard LCA. The decrease in these PV scenarios comes from the 2020 CH_4 DGWI of 26, which is lower than the standard 100-year GWP value of 28. Across all technologies, the

5% discount rate consistently produces the largest increase in present value, as it represents the most aggressive increase in social costs of future emissions. Following the 5% scenario, the 3%-95th, 3%, and 2.5% scenarios have varying impacts based upon the mix of greenhouse gases in construction and operational phases.

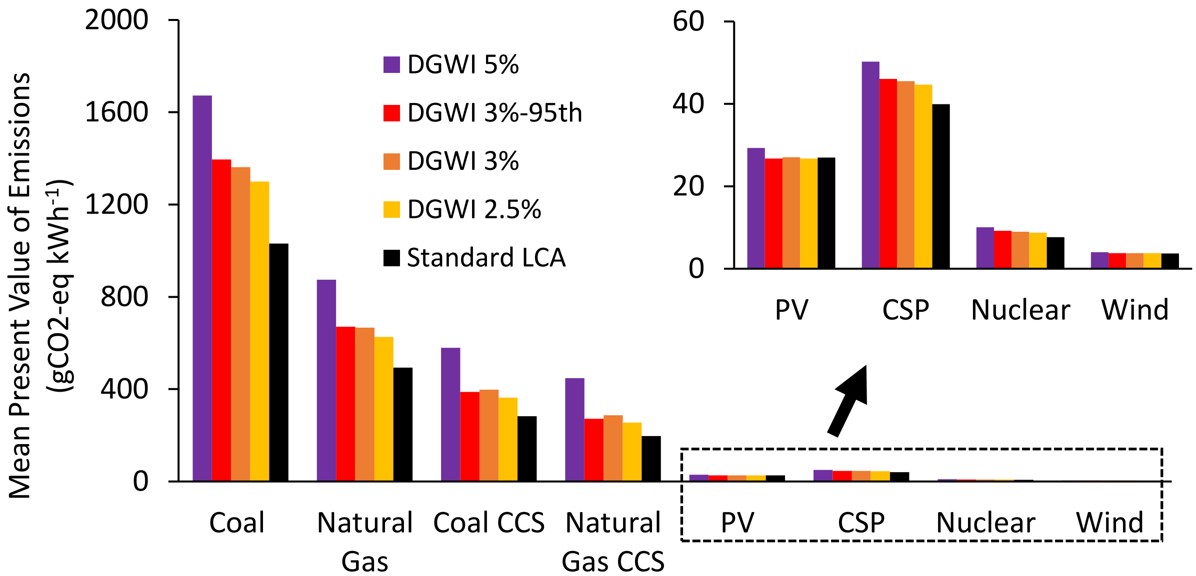

Figure 3.1. *Monetized Impact of Energy Technologies: Mean present value of emissions for electricity generation technologies based on DGWI values corresponding to 2.5%, 3%, 3%-95th percentile, and 5 % social cost discount rates.*

When considering construction compared to operational emissions, it is important to recognize that the majority of emissions from fossil-based technologies occur during operation. This makes the mean present value of fossil-based technologies especially sensitive to temporal impact. Thus the technology with the largest increase in emissions impact is coal. When using the 3% DGWI as a baseline scenario, emissions from a coal power plant increase from a standard LCA value of 1031 gCO_2-eq/kWh up to a new mean present value of 1362 gCO_2-eq/kWh. This 32% increase is primarily due to large operational emissions over the 30 years of plant operation. Technologies with lower operational emissions show a much smaller increase. For example, applying the 3% DGWI to wind power changes a standard LCA value of 3.74 gCO_2-eq/kWh to a new mean present value of 3.81 gCO_2-eq/kWh, which is an increase of only 1.9%.

Comparing the results of the baseline 3% scenario to the 3%-95th percentile scenario across coal CCS, natural gas CCS, PV, and wind shows that in these cases the 3%-95th percentile have a slightly lower impact than the 3% scenario. For coal CCS and natural gas CCS, this is the result of significant operational CH_4 and N_2O emissions. These emissions are weighted by the CH_4 and N_2O DGWI values which are lower for the 3%-95th scenario than the 3% scenario across all years as shown in Table 3.4. For wind and PV, the majority of emissions occur during construction in the first year. Again, looking at the DGWI values in Table 3.4, the CH_4 and N_2O values in the initial year are lower for the 3%-95th scenario, leading to a slightly lower overall impact. In general, it is important to reiterate that the change in emission values associated with the mean present value does not represent a physical change in the quantity of greenhouse gases emitted. Instead, these values represent emissions that are scaled by their impact relative to the present year of analysis.

Applying the DGWI to the temporally resolved emissions of guayule rubber production result in Figure 3.2. The standard emissions of guayule rubber production are 10.48 kg CO_2-eq per kg of rubber, which is slightly above the 10.3 kg CO_2-eq per kg of rubber found in the previous chapter. This slight increase in standard emissions is due to the two initial startup years where guayule is being grown, but rubber is not produced, which was excluded from the initial analysis. Applying the DGWI to temporally resolved emissions increases the mean present value of emissions. The baseline 3% discount rate yields 14.58 kg CO_2-eq per kg of guayule rubber. This 39% increase in emissions is the result of weighting emissions in future years with greater socio-economic impact. Similar to a fossil fuel based power plant, the significant operational emissions associated with rubber extraction make guayule rubber particularly sensitive to the application of the DGWI.

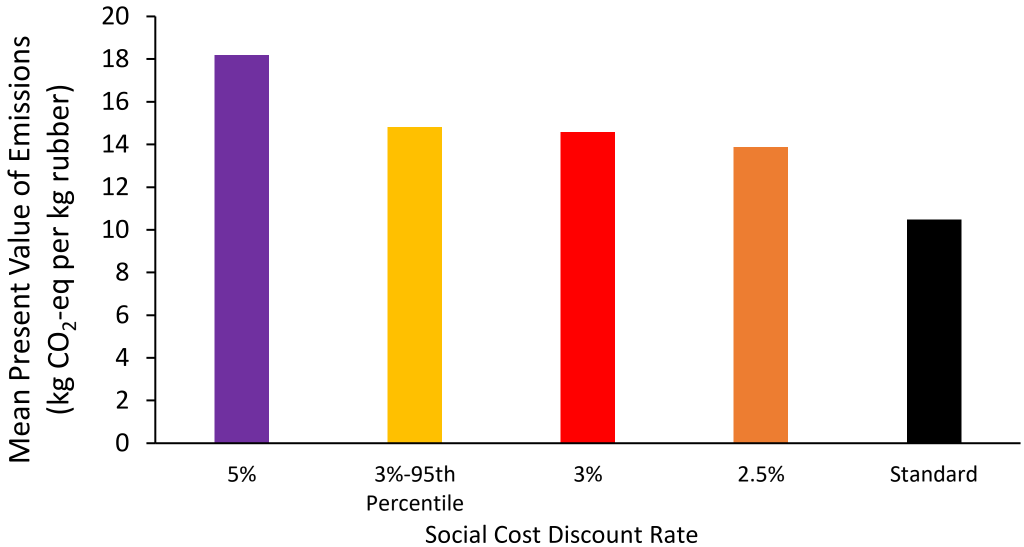

Figure 3.2. *Mean present value of emissions for guayule rubber production based on DGWI values corresponding to 2.5%, 3%, 3%-95th percentile, and 5 % social cost discount rates.*

3.3.2. Incorporating the Social Cost of Carbon in TEA

Figure 3.3 displays LCOE results with and without social costs of greenhouse gases. Across all electricity generation technologies considered the 3%-95th percentile discount rate has the largest impact on LCOE followed by the 2.5%, 3%, and 5%, respectively. The largest rise in LCOE occurs in coal where a standard TEA LCOE of 9¢$_{2020}$ kWh^{-1} changes to a LCOE of 16¢$_{2020}$ kWh^{-1} for the baseline 3% scenario. This 88% rise is primarily due to long-term operational emissions over the 30-year lifetime of the coal power plant. For comparison, a technology with lower operational emissions, such as wind, shows just a 1% increase, changing from a standard LCOE of 5.58¢$_{2020}$ kWh^{-1} to a new LCOE of 5.64¢$_{2020}$ kWh^{-1} when the costs of greenhouse gases are included.

Figure 3.4 shows the effect of applying the social costs of greenhouse gases to guayule rubber production in the baseline scenario and in the on-site heat and power scenario. In the baseline scenario, the minimum selling price rises from a standard TEA value of \$3.08 per kg rubber up to \$5.51 per kg rubber in the 3%-95th percentile social discount rate scenario. This 79% increase in price represents the additional revenue that must be generated to offset the social costs of greenhouse gases. In the on-site heat and power scenario the standard TEA results in \$4.07 per kg rubber, while the 3%-95th percentile discount rate social costs increase the cost to $4.37 per kg rubber. The on-site heat and power scenario sees a smaller increase than the baseline scenario because bagasse combustion reduces the overall greenhouse gas emissions of guayule production. Therefore, the on-site heat and power scenario is able to avoid significant emissions costs and maintain a lower minimum rubber selling price when 2.5% and 3%-95th percentile social costs are included. These results highlight how incorporating social costs of greenhouse gases within an integrated TEA and LCA analysis can change or even reverse findings from a standard TEA. In this case, monetizing emissions and including them in TEA has resolved the economic and environmental trade-offs of combusting bagasse. In doing so, the new method has helped identify future scenarios where bagasse combustion would be the better option environmentally and economically.

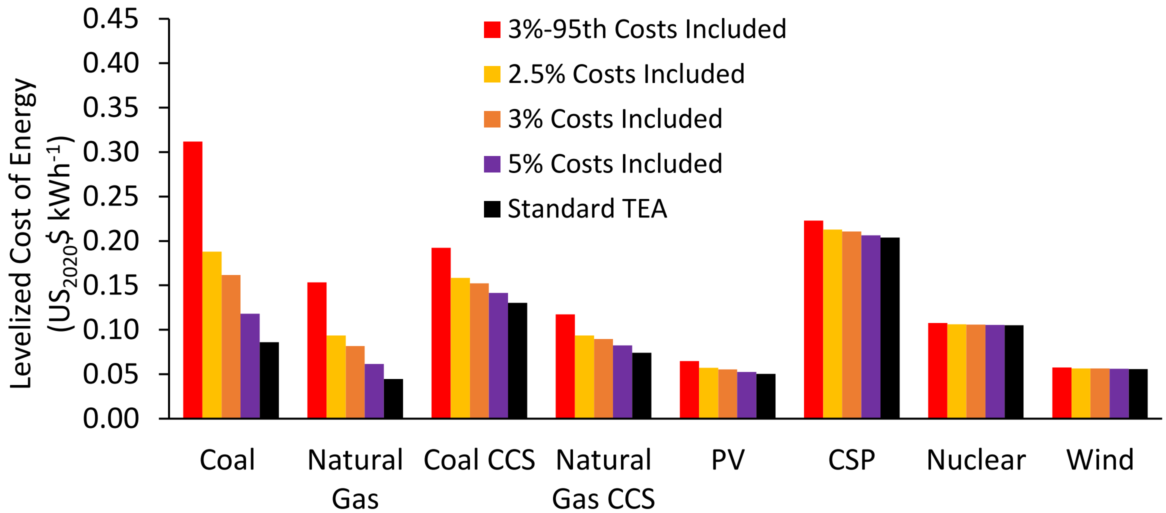

Figure 3.3. *Economic Impact of Integrating Emissions: LCOE of electricity generation technologies including social cost of greenhouse gas based operational emissions cost.*

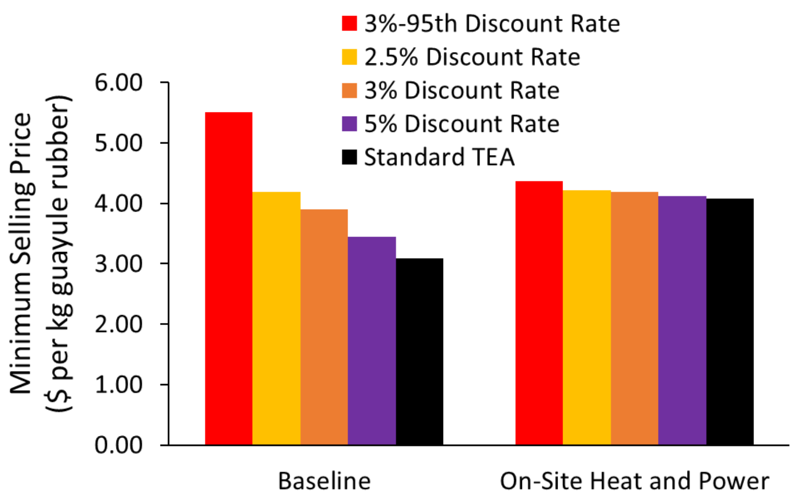

Figure 3.4. *Comparison with Social Costs of Greenhouse Gases: Minimum guayule rubber selling price for baseline and on-site heat and power scenarios when social costs of greenhouse gases are included.*

3.4. Discussion

3.4.1. Comparison to Existing Methods

The new DGWI LCA method produces results that are dissimilar to the majority of previous temporal methods. In most previous CRF based methods, greenhouse gases occurring in early years of an LCA timeframe have greater weight[56–58,60,61]. The DGWI method shows that emissions occurring in later years should be weighted with greater monetized impact. This difference is due to two major methodological factors. The first factor is the time horizon. Previous methods often use a near term time horizon that causes early emissions to have a greater cumulative impact than later emissions. By leveraging the social cost of greenhouse gases, the new method also inherently includes a time horizon. However, this horizon is the year 2300, extending beyond the time horizon of many previous methods. Using the long-term time horizon reduces the impact of residence time, but does not entirely remove it. The second factor causing a difference is the inclusion of social damages. Previous studies have typically relied upon CRF or global temperature change as the metric for impact. The DGWI goes several steps beyond CRF and temperature to include biological impact, economic impact, and other factors. The expected exponential increase in these damages causes later emissions to have a higher monetized impact.

This increase exceeds any reduction caused by the time horizon or decreased radiative efficiency due to increasing greenhouse gas concentrations.

The TEA methods in this research follow an increasing number of studies that include environmental externalities in economic calculations. However, other studies typically do not include individual costs for temporally resolved emissions of CO_2, CH_4, and N_2O. Instead, they utilize 100-year GWP values to equate greenhouse gas emissions to CO_2 and then apply a single time independent external cost for CO_2-eq emissions[86]. One of the more comprehensive studies goes a step further to include temporal resolution in CO_2 and CH_4 costs, but still utilizes CO_2-eq within certain calculations [87]. Determining which methods are most appropriate for a cost-benefit analysis will largely depend upon how global social damages are applied to industry through mechanisms such as a carbon tax.

3.4.2. Limitations and Implications of Methods

The methods presented in this phase demonstrate two different approaches for quantifying temporal impacts of greenhouse gas emissions. Both methods are based on the social costs of greenhouse gases, which come with inherent limitations. The most prominent limitation is the uncertainty of future climate, social, and economic systems. One major element of uncertainty has been captured by including a range of economic discount rates provided with the social cost values. This and other elements of uncertainty are addressed thoroughly within the technical documentation provided by the IWG on the Social Cost of Greenhouse Gases[70,74,75]. The IWG authors outline their use of multi-model ensemble, probabilistic analysis, and scenario analysis to address uncertainty by obtaining frequency distributions for the social costs of greenhouse gases. The numbers used in this research are the central estimates of those distributions. Future development of these new methods could benefit by propagating the social cost distributions through analysis of temporally resolved LCA.

Beyond uncertainty, another limitation of the social cost estimates is that they represent the cost of marginal emissions. As a result, they convey the damage of a one-ton emission on top of a predetermined global emissions scenario. Therefore, these values cannot be used to predict the damage from changes that would significantly alter global emissions. Performing such an analysis would require varying the global emissions scenario within the IAM. As a result, the methods in this phase of research are limited to analyzing scenarios that will not affect global emissions trajectories. In the case of electricity production, these methods are used to compare the construction and operation of specific power plants. The results should not be interpreted as the average impact of altering the global or national electrical grid mix with these technologies.

Although limitations exist, the results of these new methods have some important implications for the future of dynamic LCA. First, the current dynamic LCA practice of comparing CRF up to a given time horizon results in findings that are opposite of monetized social damage estimates. This does not mean current dynamic LCA practice is incorrect, but it does force us to consider the purpose of this methodology. Considering impacts up to a given time horizon prioritizes the importance of certain emissions relative to a given time-frame. This approach does make sense if the intent is limiting near term global temperature rise to avoid climate tipping points. However, if the intent is to compare the actual long-term impact of a technology then the social cost methods provide a more comprehensive basis for comparison.

A second implication is the substantial effect of translating mid-point metrics such as quantities of greenhouse gases into end-point metrics such as economic damage. In the example of electricity generation, using the DGWI in place of the GWP can change the result of coal power by up to 62% in the most severe scenario. Change of this magnitude could significantly alter a comparison between technologies. The inclusion of these end-point metrics undoubtedly comes with an increased level of uncertainty as mentioned above. However, this uncertainty is common within existing LCA, climate science, and economic practice. As a result, new methods are under constant development to address uncertainty in these fields.

The results of this work demonstrate that the inclusion of temporal considerations and monetized impact can dramatically alter comparisons between technologies. Based upon these results, several recommendations should be considered. First, it is important that LCA data and results include temporal resolution. Averaging data or making assumptions regarding the timing of emissions can introduce significant differences and skew results. Second, when comparing technologies in LCA or TEA, methods such as the two presented in this research should be used to compare temporal impact. The selection of a specific method will be dependent upon the context of a particular comparison. Third, further work needs to be carried out to identify other technologies beyond electricity generation where temporal resolution can dramatically change results. There may be existing analyses where inclusion of temporal impact reverses an established conclusion.

3.5. Conclusions

Two new methods were created to integrate TEA and LCA while addressing the major disconnect of temporal resolution. The application of these methods to multiple technologies highlighted how this integrated approach can be used to pull greenhouse gas emissions into TEA. Furthermore, it confirms that including these emissions within TEA can significantly alter results, especially when including temporal resolution. The largest limitation of these new methods is the uncertainty associated with the future of climate change and global economic systems. As a result, it will be critical to look at multiple future scenarios where idealistic social costs of greenhouse gases are compared to more realistic implementation of a carbon tax. The following chapter includes this sort of comparison by evaluating multiple emissions pricing scenarios. In addition, the next chapter will take a deep dive into a specific application where these sort of combined TEA and LCA methods can be especially beneficial to answering questions associated with increasing ambitious global climate goals.

CHAPTER 4: APPLYING NEW TEA AND LCA METHOD TO NGCC POWER PRODUCTION[c]

4.1. Background

The abundance and low cost of natural gas have made it the primary fuel source for electricity generation in the United States[88]. Growth of natural gas combined cycle (NGCC) electricity generation capacity is expected to continue, with 6.7 GW of new power planned for 2020[89]. The addition of further natural gas power plants coincides with the steady retirement of coal and a corresponding reduction in greenhouse gas emissions from fossil fuel electricity generation. However, the added natural gas capacity also represents a potential continued dependence on fossil fuels for decades to come, as these plants have a typical lifetime between twenty and thirty years[90,91]. Within this same timeframe, the Intergovernmental Panel on Climate Change (IPCC) has demonstrated that a sharp decline in greenhouse gas emissions toward net-zero which is considered necessary to maintain consistency with the aims of the Paris Climate Agreement, including holding the increase in the global average temperature to well below 2°C above pre-industrial levels[92,93]. National-level net-zero emissions targets are also being implemented by an increasing number of countries, reinforcing this policy direction[94,95]. The necessary shift in energy generation requires increased deployment of low-emitting energy sources and a decisive attenuation of emissions-intensive energy sources including electricity derived from natural gas. The continued deployment of natural gas generation capacity therefore poses environmental and economic risks, through carbon lock-in and the potential for stranded assets[96,97].

A range of technologies have been proposed that could be deployed in existing NGCC power plants to reduce their greenhouse gas emissions. One class of options is fuel switching, including to renewable gases such as biomethane or hydrogen that are being considered as low-emissions substitutes for natural gas[98,99]. Biomethane can be generated through thermochemical conversion or sourced from

[c] This chapter was submitted for publication as a peer-reviewed journal article: E. Sproul, J. Barlow, J.C. Quinn, "Technology Options for a Natural Gas Power Plant Stranded in a Net-Zero Emissions Environment," Environmental Science & Technology, Submitted June 2020.

natural biological decomposition occurring in processes such as agriculture, waste-water treatment, or solid waste management. Upon upgrading, biomethane can directly replace natural gas and be used in existing infrastructure such as natural gas pipelines and NGCC power plants. Therefore, biomethane avoids many of the storage, distribution, and combustion challenges associated with other gases such as hydrogen, which are likely to require new infrastructure[100–102]. The estimated full-scale production and distribution costs of biomethane vary widely, with projections ranging from below \$10 per mmBTU to above \$20 per mmBTU[103,104]. Costs of natural gas in the United States have hovered around \$2 per mmBTU for the past year, making it a challenge for biomethane to compete without some sort of economic incentive based on emissions[105].

In addition to alternative fuels such as biomethane, there has been a large amount of research surrounding post-combustion carbon capture and storage (CCS). A number of technology options exist for CCS, but the most common use an amine solvent to capture and remove CO_2 from power plant flue gases so that it can be injected and stored in large geological reservoirs[106]. Combining this technology with bioenergy sources results in bio-energy with carbon capture and storage (BECCS), which has the potential for net-negative CO_2 emissions[107]. The deployment of BECCS is often foreseen in emission reduction pathways where sequestration of atmospheric CO_2 is needed. However, specific pathways for full scale deployment of BECCS remain largely undefined, causing an ongoing discussion regarding the challenges and opportunities associated with the concept[108–110].

As technologies such as biomethane, CCS, and BECCS continue to evolve, they are being evaluated from a wide variety of perspectives. Within the engineering community these technologies are often evaluated using TEA. A number of TEAs have been performed individually on different pathways for both biomethane and CCS[111–116]. TEAs of specific pathways for BECCS also exist but are less common[117]. Generally, TEAs are centered on evaluating a specific pathway to enable deployment of a single new technology. It is less common to consider multiple technologies within the context of existing infrastructure, such as a NGCC power plant. However, in the case of biomethane, CCS, and BECCS, using the TEA of an existing NGCC power plant to evaluate these technologies has two distinct advantages. First, the existing infrastructure of the power plant can help avoid the up-front capital costs associated with an entirely new project. Second, upgrading an existing facility to one of these technologies will help mitigate greenhouse gas emissions for the remainder of the NGCC plant lifetime, thus reducing the risk of carbon lock-in and the plant becoming a stranded asset. However, addressing this second advantage within the context of TEA presents challenges, as there is no standard price on emissions within the United States. As a result, a range of theoretical prices must be considered to capture the emissions benefits of technology options within the context of potential future policies.

Emissions pricing is not the only unknown within TEA, as many of the costs associated with biomethane and CCS remain undefined. Therefore, solving a TEA for a levelized cost of electricity (LCOE) will inherently contain uncertainty. In cases of large uncertainty, such as biomethane and CCS, it is beneficial to define the cost of electricity based on current market data and solve for capital and operational cost targets. While this is not common in TEA of electricity generation, a similar concept has been demonstrated in the context of bioprocessing[118]. Defining cost targets will provide a baseline reference of economic viability for future technological development of biomethane, CCS, and BECCS. In addition, using the cost target method across these technologies limits the uncertainty of the analysis to changes in electricity market prices, which can be grounded through analysis of historical data.

This research uses a cost target TEA approach to explore the technology options of biomethane, CCS, and BECCS adopted within an existing NGCC power plant. In this approach a 30-year TEA is developed to track the costs and benefits of adopting the technology options at different years. Using the TEA, cost targets are developed by comparing the technology options to a baseline scenario in which the NGCC plant is operated normally for the remainder of its life, as well as a shutdown scenario where the power plant is decommissioned before its scheduled end of life. Novel contributions of this work include: 1) A publicly available TEA model for an existing NGCC plant which includes the adoption of low-emissions technology options, temporally resolved LCA emissions data, and temporally resolved emissions pricing. 2) Cost targets for biomethane, CCS, and BECCS that will allow these options to compete with baseline and shutdown scenarios. 3) Evaluation of multiple emissions pricing scenarios and their effect on low-emissions technology cost targets. These contributions will help inform options for existing natural gas power plants, direct the development of low-emissions technologies, and highlight the effects of including emissions pricing within TEA.

4.2. Methods

The methods of this work have been separated into four primary sections. The first three details the development of a modular NGCC TEA with time resolved LCA data and emissions pricing scenarios. The TEA includes options for switching to a biomethane fuel source, adding CCS, or adopting both to create a BECCS system at any year between 2025 and 2040. The fourth section applies the modular TEA to evaluate multiple emissions pricing scenarios and identify biomethane, CCS, and BECCS cost targets.

4.2.1. Development of Techno-Economic Analysis

The TEA developed for this work tracked the discounted cash flows of a NGCC power plant over a lifetime of 30 years. The TEA was based on standard techno-economic methods that have been used to evaluate a range of new and existing energy technologies[3,85,119]. The primary data source for the TEA was the National Renewable Energy Laboratory (NREL) 2019 Annual Technology Baseline (ATB)[85]. Data from the NREL ATB was used to inform economic parameters and operational costs of the NGCC power plant with and without CCS. An additional reference from literature was used for decommissioning costs as this was not available within the NREL ATB[120]. The key economic parameters used within the TEA are presented in Table C.1. The TEA was developed to have variable input parameters (fuel costs, heat rate, CCS capital costs, electricity prices, capacity factor, adoption timing, and greenhouse gas emissions pricing) in support of the different evaluations presented in section 2.2. All economic analyses are calculated in 2020 U.S. dollars.

4.2.2. Life Cycle Greenhouse Gas Emissions

NGCC greenhouse gas emissions were estimated using previous LCA data from the National Energy Technology Laboratory (NETL)[77]. Emissions included the construction, commissioning, operation, and decommissioning of a NGCC power plant, as well as installation, construction, operation, and deinstallation of domestic onshore natural gas well sites and pipeline. All emissions were temporally resolved across each year of power plant construction and operation. Construction emissions were divided equally across the three years of plant construction. Well site and pipeline emissions were evenly distributed over the thirty-year lifetime of the facility, as the installation and deinstallation of natural gas infrastructure to support a power plant were considered on-going. Across the well-sites and pipeline, fugitive methane emissions were revised to 2.3% to reflect an updated assessment by Alvarez et al[78]. Biomethane production emissions are dependent upon source and upgrading method[99,121]. For this work, 25 g CO_2 per MJ was attributed to the production and combustion of biomethane to represent a central estimate from multiple sources. Data for individual contributions of CH_4 and N_2O to biomethane production were not found in literature, and were not included in this analysis. Upon addition of CCS, the CO_2 emissions from combustion of natural gas or biomethane were assumed to be reduced by 90%.

4.2.3. Greenhouse Gas Emissions Pricing

Two separate sets of emissions prices were used within the analysis. The first were the social costs of greenhouse gases developed by the Interagency Working Group on The Social Cost of Greenhouse Gases[74,75]. These costs represent the discounted marginal economic damage to society caused by a one metric ton emission of CO_2, CH_4, or N_2O in a given year. The discount rate selected for future damages has a significant impact on the social costs. Within the TEA, 5%, 3%, and 2.5% social cost discount rates were included, with the central 3% estimate being used for the results of this research. The second set of emissions prices used in this TEA were defined within the Energy Information Administration's (EIA) Annual Energy Outlook (AEO)[88]. The EIA describes these prices as a carbon allowance fee starting at a base value of either \$15, \$25, or \$35 per metric ton in the year 2021 and rising by 5% each year out to 2050[122]. As with the social costs, the TEA was developed with options for all three base values, but the central price series beginning with \$25 per metric ton in 2021 was used for the results in this research.

Each of the emissions prices was applied in a manner consistent with their development. The social costs of greenhouse gases were applied individually to any CO_2, CH_4, or N_2O emissions associated with the NGCC plant or upstream fuels production. Any net-negative emissions occurring within the

BECCS system were credited with a positive value. The EIA carbon fee was embedded in the natural gas pricing structure associated with the carbon fee scenario. As a result, no additional fee was applied to natural gas within the NGCC plant. However, as no price structure exists for biomethane, the EIA fee was applied to CO_2 emissions from upstream biomethane production to ensure consistency with natural gas. In addition to natural gas pricing, electricity pricing is a critical consideration when applying the EIA fees. Within the EIA carbon fee scenarios, the EIA modeled United States sector-wide application of the carbon fee and a corresponding increase in electricity price resulting from demand changes and pass-through of the carbon fee into electricity prices. However, this increase in electricity prices is highly dependent upon the overall grid mix and the uncertain future of renewables, which has exceeded expectations to date. As a result, in this model the application of the EIA carbon fee was accompanied by two scenarios. In the first, projections for market prices of electricity were kept consistent with the EIA AEO reference case to demonstrate the economic impact of carbon fees directly on the isolated NGCC power plant under analysis. In the second, projections for electricity price were increased to match the EIA $25 carbon fee case in which macro-level feedback effects were modeled by the EIA. These two scenarios are referred to as "without feedback" (indicating electricity prices from the EIA reference case) and "with feedback" (indicating electricity prices from the EIA carbon fee case) throughout the remainder of this research.

4.2.4. Model Settings for Specific Evaluations

The analysis in this research consisted of three separate evaluations: 1) An evaluation of capacity factor to define a baseline net present value (NPV). 2) An evaluation of changing to low-emissions technology options in the year 2025. 3) An evaluation of the effect of time and emissions pricing on biomethane and BECCS cost targets. Each of these evaluations and the corresponding assumptions used within the TEA are detailed in the sections below.

4.2.4.1. Varying Capacity Factor to Define a Baseline NPV

The first evaluation focused on the effect of varying capacity factors within the existing NGCC power plant. Over recent years there has been a wide distribution of capacity factors for NGCC power plants in the United States[123]. The current average capacity factor is 58%, with projections of this average showing a decline to below 40% in future years as more renewable electricity generation sources come online[88]. Meanwhile, a small number of plants are expected to continue operating with relatively high capacity factors of 80-90% due to regional market dynamics. Selecting a baseline capacity factor from these potential scenarios was critical for comparing the performance of different technological options. As a result, three separate capacity factor projections were reviewed to define the baseline. These projections were a constant high (87%) capacity factor scenario aligning with the high capacity factor case in the NREL ATB, a constant average capacity factor (58%) projection based on 2019 EIA statistics, and a declining average capacity factor (56% in 2020 declining non-linearly to 32% in 2050) projection for existing plants based on the EIA AEO reference case. Across this evaluation, natural gas and electricity prices were set to match the EIA AEO reference case projections[88]. The heat rate of the NGCC power plant was set at 6.45 mmBTU/MWh for normal operation based on average data in the NREL ATB. Using these inputs, the cash flows of each capacity factor projection were solved for the NPV and a baseline was selected.

4.2.4.2. Low Emissions Technology Adoption in 2025 without Emissions Pricing

Using the baseline defined in Section 2.3.1, the next evaluation considered adopting low-emissions technology options in the year 2025. In the evaluation, the NGCC power plant was constructed over three years starting in 2017 and operated normally from 2020-2024. In 2025, operation was changed to one of three technology options. The first option was a fuel switch from natural gas to biomethane. This switch required placing a price on biomethane which has estimated production costs ranging from below $10 per mmBTU to over $20 per mmBTU[103,104]. This initial evaluation assumed $10 per mmBTU, which aligns with production cost estimates from a UC Davis report and a previous fixed contract price ($9.80 per mmBTU) paid by the Los Angeles Department of Water and Power[104,124]. However, this value was also varied in the analysis to demonstrate the effects of uncertainty of biomethane pricing and the potential for future technological development resulting in further cost reduction. The second option was the addition of CCS to the existing NGCC power plant. In this option the plant continued operation, but it was retrofit with CCS over the course of a year. CCS capital costs of the retrofit were set at $1797 per kW, which aligns with an average estimate used in EIA electricity models[125]. Separation and compression of the CO_2 stream using an amine solvent required increased operational costs, as well as an increased heat rate (7.53 mmBTU per MWh) associated with solvent recovery[85]. The third option was BECCS based on the combined switch from natural gas to biomethane and the addition of CCS. In this scenario, the two changes occur simultaneously (biomethane switch at the onset of the CCS construction) and the BECCS system operates from 2025 to the plant's end of life in 2050. In addition to these three technology options, a fourth option of plant shutdown was also considered. During shutdown all operations and revenue ceased immediately and the plant was decommissioned over a one-year period. The four options were each run through the TEA and solved for the resulting NPV. The results were compared across each technology option as well as the baseline case of normal operation. CCS capital costs and biomethane fuel costs were then varied to determine cost targets that result in the technology options matching the NPV of normal operation.

4.2.4.3. The Effect of Adoption Timing and Emissions Pricing on Cost Targets

Within this evaluation, multiple parameters including adoption timing and emissions pricing were varied to identify the effect on cost targets. For a switch to biomethane, 16 separate cost targets were found by varying emissions pricing and the year in which fuel switch takes place. For the BECCS system with biomethane and CCS, a total of 64 cost targets were identified by varying adoption timing, emissions pricing, CCS capital cost, fuel cost, and heat rate. Emissions pricing included four scenarios: no emissions pricing, 3% social cost of greenhouse gases, $25 EIA carbon allowance fee without feedbacks, and $25 EIA carbon allowance fee with feedbacks. Varying heat rate was included in the analysis to capture an increase in operational costs for the CCS system, which need additional energy to recover amine solvent.

4.3. Results and Discussion

For clarity, the results and discussion are broken into three sections that each detail the unique findings of running the TEA with a specific set of input parameters based on the scenarios defined in Section 4.2.4.

4.3.1. Varying Capacity Factor to Define a Baseline NPV

This initial techno-economic evaluation looked at the effect of capacity factor on the NPV of a normally operated NGCC power plant, as shown in Figure 4.1. In the figure, the initial negative slope from 2017-2019 is due to the up-front capital investment when the plant comes on-line. The slope changes in 2020 when operational revenue comes online and again in 2030 when the capital loan is paid off. The difference in trajectories and ending NPV between the three curves is the result of varying the capacity factor. The capacity factor directly affects the annual revenue of the plant which is the functional unit and thus has a pronounced impact. Varying the capacity factor between scenarios changes the NPV of the plant by as much as $912 per kW, with the system ranging from -$62 per kW to $850 per kW for the low and high capacity factor scenarios. The facility has a NPV of zero with a constant capacity factor of 47%, meaning anything below this causes NPV to drop below zero at the end of life. The constant average capacity factor of 58%, which yields a NPV of $234 per kW, was selected as the baseline scenario and defines normal operation of the plant across this research phase. This baseline was selected to avoid an overly optimistic scenario represented by the constant high capacity factor and the uncertainty of future projections contained within the declining average capacity factor. While the capacity factor impacts the results of the following evaluations, the overall trends would remain largely similar with the selection of a different baseline capacity factor.

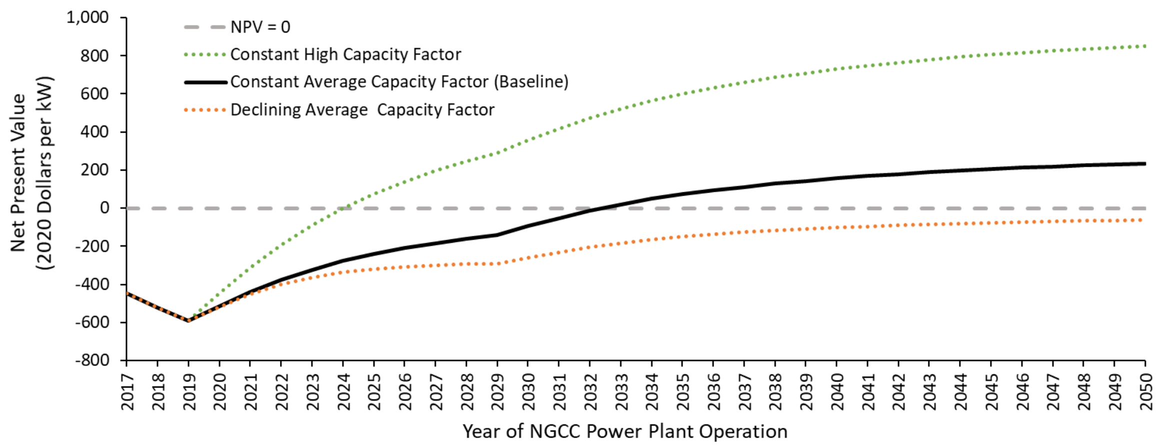

Figure 4.1. *NPV of NGCC plant with constant high (87%), constant average (58%), and declining average (56-32%) capacity factors over the life of the plant. The NPV of the constant average capacity factor scenario is considered the baseline for the analysis in this research phase.*

4.3.2. Low-Emissions Technology Adoption in 2025 without Emissions Pricing

This evaluation was used to review the impact of adopting low-emissions technology options in the year 2025. Figure 4.2 displays the NPV for normal operation, shutdown, and the three low-emissions technology options without emission pricing policies. Changing from normal operation of the NGCC power plant to any of the three low-emissions technologies will result in a negative NPV. Switching to biomethane at $10 per mmBTU is the cheapest of the technology options, but still yields a NPV significantly worse than shutdown. Addition of CCS represents a large cost as seen in the large negative slope in 2025 and results in a NPV less than -$1000 per kW at the end of life, making both CCS alternatives (natural gas and biomethane) uncompetitive. The modeling work assumes biomethane and CCS costs based on existing literature, as there is ongoing technological development in these areas to reduce costs. Due to the uncertainty of these costs, further work was done to understand the impact of varying these costs and identify cost targets that would make biomethane, CCS, and BECCS options yield a NPV equal to the baseline of normal operation.

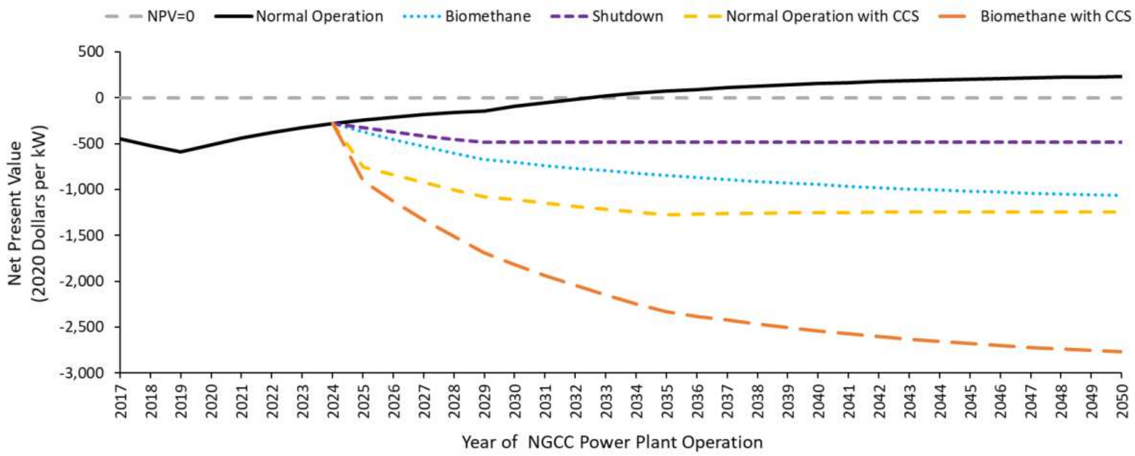

Figure 4.2. *Comparison of continuing normal operation of natural gas power plant (black line) and shutdown (purple line) with changing to one of three different technology alternatives in the year 2025. Viable options would either meet or exceed the NPV of normal operation.*

The significant effect of varying biomethane fuel costs for the NGCC power plant is presented in Figure 4.3. Reducing fuel costs from \$10 per mmBTU to \$3 per mmBTU increases NPV by \$1437 per kW and represents an economically viable solution. A fuel cost of \$3.80 per mmBTU will match the baseline NPV of normal operation. The actual production costs of biomethane are dependent upon the specific method of production and the overall market demand for that biomethane. The \$3.80 per mmBTU cost target falls well below most current estimates for biomethane production. It is important to note that while biomethane was the focus of this analysis, any readily-substitutable fuel produced at or below \$3.80 per mmBTU would provide a viable substitute when emissions pricing is not included. However, the emissions associated with a fuel other than biomethane would have impacts on the emissions pricing evaluations presented in later sections.

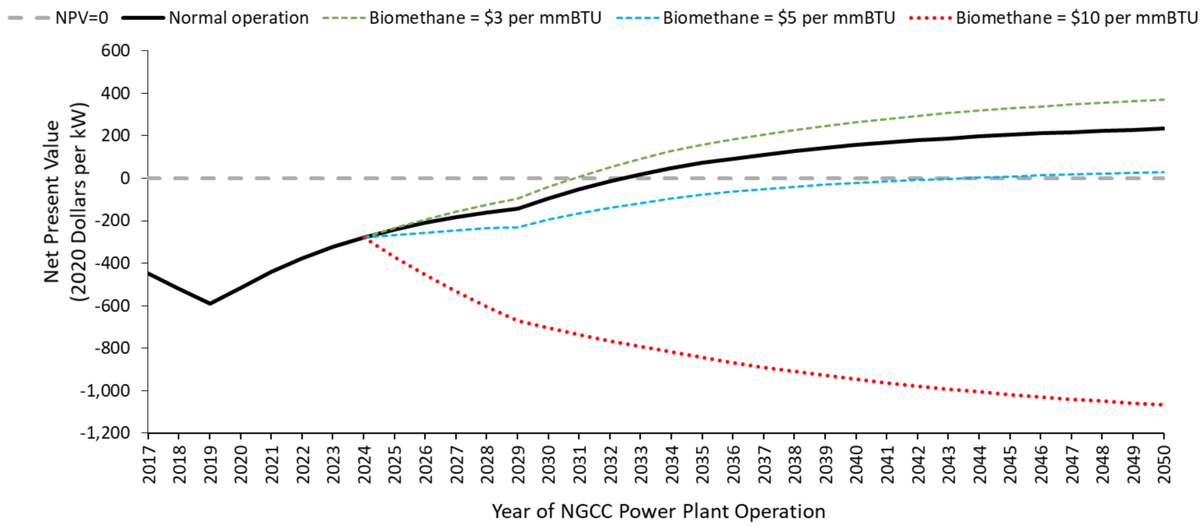

Figure 4.3. *Net present value of normal plant operation with natural gas compared to operating with biomethane at three different biomethane fuel costs.*

A cost target was also identified for adding CCS to the existing NGCC power plant. Defining this target required varying the CCS capital cost and plant operational costs (fuel cost and the heat rate of the NGCC plant after CCS was added), since each of these represents a critical uncertainty of future technological development. Figure 4.4 shows the cost target result for the addition of CCS. Costs inside the purple shaded region of the figure will result in a NPV equal to or higher than normal operation. It is important to note that in this specific evaluation the fuel cost can be the cost of natural gas, biomethane, or another equivalent drop-in fuel. In later evaluations, the use of emissions pricing will not allow for this simplification. Figure 4.4 highlights that the cost target for CCS capital is below current cost estimates which the EIA places between $1313 and $2533 per kW[125]. Even at a fuel price of $0 per mmBTU, the CCS capital costs required to compete with normal operation must be at or below $967 which is 26% less than the low end of the current EIA range. This result further confirms the findings of Figure 4.2 and demonstrates that new technologies such as CCS face a significant economic challenge without economic incentives such as emissions pricing.

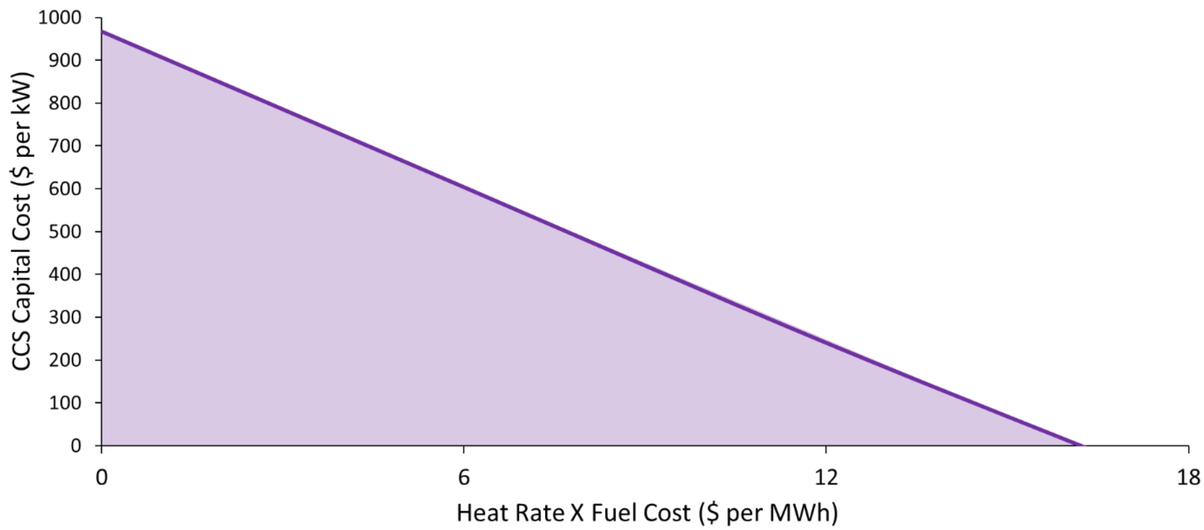

Figure 4.4. *Cost targets for addition of CCS to existing NGCC power plant in the year 2025. Points inside the targets (purple shaded region) will yield a NPV higher than that of normal operation defined in the baseline scenario.*

4.3.3. The Effect of Adoption Timing and Emissions Pricing on Cost Targets

The relationship between adoption timing, emissions pricing, and biomethane cost targets are presented in Figure 4.5. Each point in the figure represents the maximum biomethane cost that would allow for a switch to biomethane while yielding a higher NPV than normal operation or shutdown, whichever was most economically favorable. Consideration of shutdown must be included as it often yields a higher NPV than normal operation. For example, if 3% social costs are considered, a switch to biomethane in the year 2035 would be viable if biomethane costs were below $4.95 per mmBTU. Anything above this cost would result in a lower NPV than shutdown and would not be economically viable. Further clarification regarding comparisons to both shutdown and normal operation can be found within Figures B.1-B.4 of the appendix.

In Figure 4.5, two major trends are apparent. The first is that adding a price to emissions raises the biomethane cost targets when compared with no emissions pricing. The second major trend in Figure 4.5 is illustrated by the slopes of the cost target lines across the different scenarios as a function of technology adoption year. In the scenario with no emissions pricing (blue line), the upward slope of the line indicates that a fuel switch to biomethane should be delayed to decrease the impact of biomethane prices within the analysis. This would result in higher life-cycle greenhouse gas emissions. Conversely, in the social cost scenario (red line), the downward trend of the line indicates that biomethane should be adopted as early as possible to mitigate the large costs of near-term greenhouse gas emissions. This demonstrates, in idealized form, the desired effect of an emissions price to incentivize emissions reductions. The EIA $25 carbon fee with and without feedback show two different results. First, the scenario without electricity price feedback shows that the cost target peaks in 2035 and then starts to decline in later adoption years. The scenario with electricity price feedbacks does not decline after 2030, meaning the target increases over time, similar to the no price on emissions scenario, but at a higher price point due to the applied price on emissions. The difference between the scenarios with and without feedbacks after 2025 is the result of large differences in NPV due to expected electricity prices. The scenario with feedbacks will make more revenue from electricity, which compensates for the emissions price, and thus encourages a delay in the switch to biomethane. The situation without feedbacks will not benefit from this increased revenue, leading to the lower cost targets in later years, incentivizing an earlier switch to biomethane.

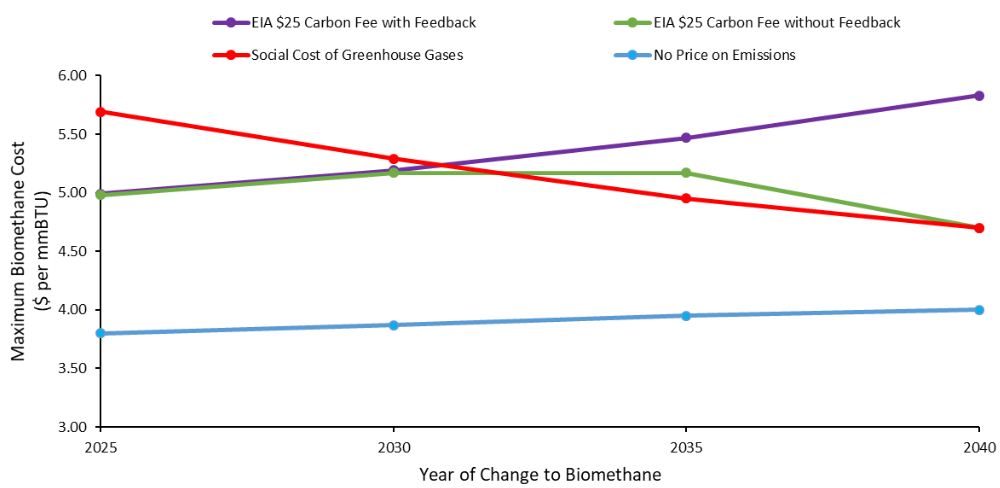

Figure 4.5. *Maximum cost targets for biomethane based on varying fuel switch year and emissions pricing scenarios. A negative slope indicates that an earlier switch to biomethane is favorable.*

Implementing both a biomethane fuel switch and CCS results in BECCS. Cost targets for this combined conversion are shown in Figure 4.6, where points below the cost target lines are considered viable. A full list of all cost targets broken down by heat rate and fuel price is located in Tables C.2-C.5 of the appendix. In Figure 4.6, all CCS capital cost targets without emissions pricing are narrow, meaning implementation of BECCS is unlikely and requires incentives such as emission pricing in order to be economically viable. The application of emissions pricing expands the targets, even bringing some in line with current estimates of CCS capital costs ($1313 - $2533 per kW)[125]. Figure 4.6 also highlights the importance of the heat rate and biomethane fuel costs, which make up the major operating costs of the BECCS system. If the addition of CCS requires more fuel (increased heat rate) for solvent recovery processes, the CCS capital costs or biomethane fuel cost must be reduced to compensate. Similarly, if the biomethane fuel cost is high, the heat rate or CCS capital cost must be reduced.

Each emissions pricing scenario has its own unique set of cost targets. When no emissions pricing is applied (Figure 4.6A), early adoption of BECCS is advantageous at very low operational costs. However, as operational costs increase the trend is reversed and adoption should be delayed. When social costs are applied (Figure 4.6B) the adoption of BECCS should occur as early as possible to allow for the widest target. The EIA $25 scenarios with and without feedback each have their own unique implications. In the EIA $25 without feedback (Figure 4.6C), adoption in 2030 results in the largest target when heat rate and fuel costs are low. However, as operational costs increase, the impact of timing shifts and suggests later adoption would be preferred. Last, the EIA $25 with feedback (Figure 4.6D) shows the cost target for adoption in 2035 is widest at low operational costs. However, similar to the other EIA scenario, as fuel costs and heat rate increase, delaying BECCS adoption becomes the better option, a trend that is counter to reducing emissions in the near term.

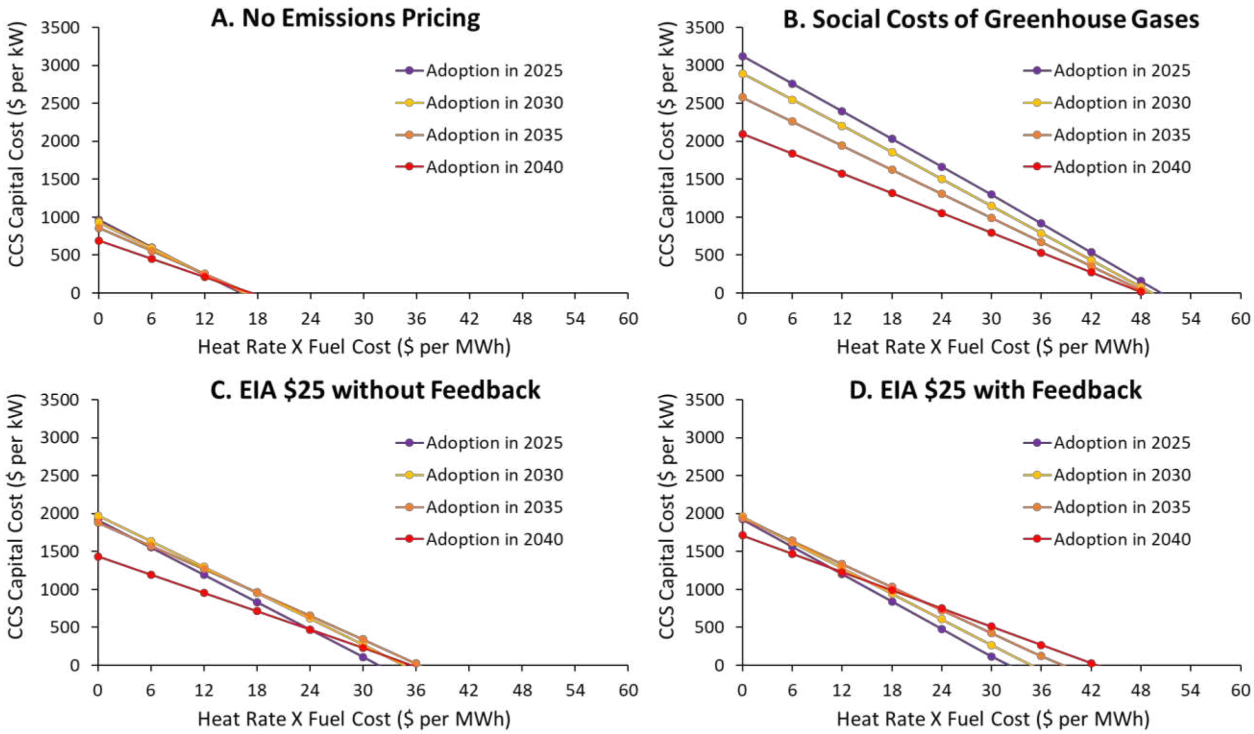

Figure 4.6. *BECCS cost targets varied across emissions pricing scenarios and adoption timing. Vertical axis represents capital costs associated with CCS retrofit. Horizontal axis shows major operational costs as defined by the biomethane fuel cost multiplied by the heat rate of the power plant with CCS.*

A comparison of 4.6A and 4.6B illustrates the effect of an idealized application of greenhouse gas emissions pricing: the required costs for low-emitting alternatives increase to competitive ranges and their adoption is incentivized earlier in time. Numerous other emissions pricing scenarios, with variations in price level and scope, could be applied between the extremes examined in 4.6A and 4.6B. The EIA scenarios (4.6C, 4. 6D) are used in this work to illustrate one such plausible application. The findings in 4.6D demonstrate how potential macro-level feedbacks affect the cost targets and decision timing, with a switch to BECCS disincentivized by increased electricity prices and changes in fuel mix in the electricity generation sector as a whole. It must be acknowledged that this "with feedbacks" scenario relies on the EIA's modeling of an economy-wide application of an emissions price and carries the Administration's own views of the future of the electricity generating sector, which affects the evaluation presented. It nevertheless highlights that macro-level effects have the potential to alter technology decisions, sometimes negatively if the aim of the emissions pricing policy is to incentivize emissions reductions consistent with a net-zero world.

The comparisons in Figure 4.6 also highlight critical areas for development in TEA methodology, where it is anticipated that emissions pricing will increasingly be included. Standardized emissions prices for analysis scenarios and harmonized scope of their application could facilitate clearer comparisons among studies of technology options. Macro-level effects arising from the sector-wide application of emissions pricing, which are typically considered outside the scope of TEA, must also be addressed. In another deviation from conventional TEA, this study used future projections of electricity prices as in input, which introduced uncertainties such as market dynamics that may vary widely in real-world practice, but facilitated a useful comparison when technology options are considered alongside emissions pricing in long-term analyses.

4.4. Conclusions

The results across this research phase help define three major conclusions. First, by using standard TEA without a price on emissions, implementation of low-emissions technology options on a NGCC power plant is unlikely. From an economic standpoint, without emission pricing the best option is to run the plant out to end of life, thereby locking in emissions for the full 30-year life of the plant. The second conclusion is that integrating TEA and LCA by putting a price on emissions makes biomethane and CCS cost targets wider and more attainable. As a result, the likelihood of implementing biomethane, CCS, or BECCS while maintaining a viable NPV increase significantly. The third major conclusion is that emissions pricing can incentivize early adoption of low-emissions technologies, but its application and macro effects at sector level can actually counteract this aim. These three conclusions, as well as the cost targets identified in this work can help further the discussion surrounding existing NGCC power plants and the technological development of low-emissions options such as biomethane, CCS, and BECCS. Lastly, this research phase confirms the importance of integrating TEA and LCA while including temporal resolution. Doing so not only results in a more accurate analysis, but also provides insight that would otherwise be entirely excluded from consideration.

CHAPTER 5: OVERALL CONCLUSIONS AND FUTURE RESEARCH

5.1. Overall Conclusions

The three phases of research contained in this dissertation have identified and resolved key issues within TEA and LCA. In the first phase, standard TEA and LCA methods were used to evaluate the economic and environmental performance of guayule rubber. From this evaluation the strengths and weaknesses of the standard, disconnected methods were identified. The major limitation is the use of incomparable metrics and a total lack of temporal resolution in LCA. In the second phase, these limitations were directly addressed through the development of two new methods that integrate TEA and LCA together while including detailed consideration of temporal resolution. Applying these methods to established and emerging technologies demonstrated that including considerations of time could significantly alter the comparison across technologies. In the third phase, integrated TEA and LCA methods were used to address the rising concern of stranded natural gas power plants. The work in this phase showed that the economic performance of low-emissions technology options is largely dependent upon specific TEA and LCA methods used within an evaluation. In addition, the work identified cost targets that can help guide future technological development of biomethane, CCS, and BECCS. The cumulative result of these three research phases has been a novel exploration of integrating TEA and LCA. Further research into each of these three phases can provide additional insight into integrated TEA and LCA and application of this methodology to guayule and electricity production. As a result, the following three sections are dedicated to identifying future research for each of the topics reviewed in this dissertation.

5.2. Future Research on TEA and LCA of Guayule

The current model for guayule production is based upon input parameters sourced from literature and correspondence with industry partners. For critical parameters such as harvest yield and rubber content, the model will be greatly improved through the incorporation of experimental field trial data. Collecting this data within a single project is a challenge as guayule requires two full years to grow before initial harvest and six years before final harvest. However, this sort of data collection is already underway within the Sustainable Bioeconomy for Arid Regions (SBAR) project. Using SBAR field trial data will enable two primary improvements to the analysis covered in this paper. First, it allows for a better correlation between key parameters such as irrigation, fertilizer, harvested biomass yield, and biomass rubber content. Improving these parameters and making them interdependent upon one another would allow for improved agricultural scenario analysis and optimization. Second, the SBAR field trial data will be used to develop probability distributions for input parameters. These distributions will then be used in stochastic modeling such as Monte Carlo analysis to develop output probability distributions for results such as minimum selling price and environmental impacts.

Another area for future work is validation of the rubber extraction facility design and operation using full-scale production data. Input parameters for the current model are based upon a pilot-scale facility, existing patents, and literature. This data has been scaled up to full production largely based upon assumptions and may not consider design changes associated with a full-scale facility. As a result, there is room for improvement by working with an industrial partner that is willing to share their full-scale production data. Currently, this data does not exist as the current technology is still in the design phase. If a full-scale facility is brought online in the near future, this represents a tremendous opportunity for improving the existing model and using the model to provide immediate feedback on environmental performance.

A third area for future work on guayule is incorporating downstream modeling of guayule resin processing. Based on the work in this dissertation it is clear that the value of guayule resin is critical to overall project success. Therefore, understanding which resin products are the most valuable and modeling these pathways will greatly strengthen the initial TEA of guayule. Initial work on this topic has already started by performing a survey of potential products, their market size, and their estimated value. From this work, pesticides, amine-epoxy strippable coatings, and wood preservative coatings have all been identified as potential high-value applications. The next step in this research will be understanding and modeling the downstream processing required to transform resin into these products. This modeling will require coordination with experimental researchers who are developing these new processing pathways and are testing the effectiveness of the final products. Through this collaboration, the uncertainty of the resin's economic value can be narrowed down to a realistic range and the corresponding impact on rubber pricing can be evaluated.

5.3. Future Research on New Integrated TEA and LCA Methods

The new TEA and LCA methods developed within Chapter 3 have proven useful for evaluating emerging technologies. However, as mentioned previously, these methods have their own limitations. The largest limitation is the uncertainty of future climate, social, and economic conditions. Although the existing work addresses these to some extent through varied discount rates, there is still a need to expand upon this uncertainty component. One initial way to include uncertainty would be investigating the distributions of social cost estimates across literature. Using distributions in place of the single central estimates developed by the IWG would provide a wider range of future scenarios and would be less biased toward a single modeling approach.

An additional limitation of the new integrated TEA and LCA methods is that the social costs of greenhouse gases represent marginal damages to society. As a result, they can only be applied in a small-scale application that is not expected to influence overall global emissions trajectories. Therefore, applying this methodology on a larger sector-wide basis must involve integration with some sort of large scale IAM. Given the complexity of IAMs, any integration with temporally resolved LCA should take place within the IAM environment. As a result, this effort would require a full research team that is already familiar with the IAM environment and can identify the appropriate methods for incorporating temporally resolved LCA data. Once temporally resolved data is incorporated into the IAM, it would be possible to evaluate technologies that may impact an entire sector such as electricity generation, heavy industry, or transportation. In doing so, the IAM could be used to identify optimal pathways for technology development with a focus on the timing of development and deployment.

An additional opportunity related to the methods of Chapter 3 is a thorough comparison between social costs of greenhouse gases and actual carbon tax structures. The social costs of greenhouse gases represent estimates of actual damage to society based on certain climate and economic conditions. Meanwhile, a more realistic emissions pricing mechanism, such as a carbon tax, represents a policy tool to actually alter these conditions and improve current circumstances. As a result, implementation of a carbon tax will look different than the social costs of greenhouse gases. For example, a carbon tax may aim to mitigate immediate near term emissions, thus placing a high cost on near-term emissions that drops over time as the near-term goals are met. Conversely, it might instead start at a relatively low value to avoid shocking the economy with a large unforeseen cost. This low value could then be ramped up over time as the economy adapts to this new way of doing business. Regardless of what the actual policy looks like, it is clear that it will not be equivalent to social costs. As a result, future work should evaluate a range of technologies with both the new social cost methods and potential carbon tax scenarios. An initial example of this was developed in Chapter 4, but this single example should be expanded upon to include more technologies across different sectors. Technologies that might yield interesting results include fuel production, transportation, and heavy industry such as steel or concrete production facilities.

5.4. Future Research on Natural Gas Power Plants

Evaluating natural gas power plants in Chapter 4 resulted in useful cost targets for technology development. The first way to build upon this work is expanding it to include other technology options for natural gas power plants. The simplest addition would be consideration of fuel blending instead of fuel switching. For example, the model currently assumes a 100% switch over from natural gas to biomethane. However, in reality natural gas and biomethane will likely be blended somewhere within an upstream pipeline, meaning the plant receives a mix of the two gases. Including this option in the model would allow for developing cost targets based upon the percent of biomethane that is blended into the fuel. Building upon this, it is important to note that hydrogen may also be blended into the fuel mix at low enough quantities to not require new infrastructure. Adding in other alternative fuels, such as hydrogen, would bring the model more in line with what is expected in the real world as transitions occur. Building upon these improvements, the model could be used to investigate a case study in a specific region. Doing so would require modifying input parameters to reflect a specific NGCC plant or a network of plants across the region. Implementing this regional analysis would inform decisions about which plants should switch to low-emissions technology options and which should be run as-is or shut down. This research requires a significant scope expansion, but could be valuable in regions where climate goals or other policies are accelerating a transition to new technologies.

Another point for future work would be investigating how results change by varying future capacity factor projections. These projections are highly dependent upon the grid mix of electricity generation sources. For example, a faster transition to renewables could require more dependence upon NGCC plants for grid stability and would drive capacity factors upwards. However, if long term battery storage can be achieved at a reasonable cost, then the need for natural gas might decline and NGCC capacity factors would drop. These are just two of the many scenarios that could greatly impact the future of NGCC power plants and the viability of low-emissions technology options. Using the existing TEA model to play out these scenarios would help inform which future decisions would reduce emissions while allowing NGCC plants to recoup the initial capital investment. Expanding upon this idea, the model could also be adopted to accommodate dynamic electricity pricing where reliability or use during high demand hours yields a higher economic value. Combining this consideration with capacity factor would help identify trade-offs between reliability, capacity factor, and greenhouse gas emissions.

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APPENDIX A

Table A.1. *Input parameters for guayule agricultural process*

Farm Breakdown		
Acres on single farm	1235	acres
Guayule adoption	15%	of farm
Cotton on farm	5%	of farm
Corn on farm	5%	of farm
Sorghum on farm	5%	of farm
Barley on farm	5%	of farm
Wheat on farm	5%	of farm
Wheat+alfalfa on farm	10%	of farm
Alfalfa hay on farm	50%	of farm
Annual Agricultural Inputs		
N- fertilizer	45	kg/acre
P- fertilizer	91	kg/acre
Flood irrigation	4934	m^3/acre
Herbicides - Prowl	4.26	liters/acre
Herbicides - Aim	0.05	liters/acre
Herbicides - Fusilade	0.59	liters/acre

Table A.2. *Input parameters for transportation of guayule from farm to rubber extraction facility*

Transportation Input Parameters		
Average farm to processing facility distance	44.27	km
Gross truck and trailer weight	36287	kg
Truck weight	9071	kg
Trailer weight	6804	kg
Payload weight	20412	kg
Average road speed	64.4	km/hr
Average load/unload speed	5.82	acres/hr
Average fuel efficiency	2.76	km/L
Truck lifetime	15	years

Table A.3. *Input parameters for guayule rubber extraction process*

Guayule Biomass Parameters		
Harvest	41667	acres/year
Yield	12	metric tons/acre
Rubber fraction	0.075	kg rubber/kg dry biomass
Resin to rubber ratio	0.65	kg resin/kg rubber
Guayule moisture content	0.1	kg moisture/kg biomass
General Facility Parameters		
Average outdoor ambient temperature	22	C
Operational days	350	days/year
Operational shifts	3	shifts/day
Operational hours	8	hours/shift
Natural gas heating efficiency	0.75	MJ heat/MJ natural gas
210: Shrub Preparation		
Shrub lost during preparation	0.03	kg out/kg in
220: Solvent Mixing		
Total solvent mixing ratio	3	kg total solvent/kg biomass
Acetone portion of total solvent	0.2	kg acetone/kg total solvent
Hexane portion of total solvent	0.8	kg hexane/kg total solvent
Solvent remaining on bagasse out of extractor	1	kg solvent/kg bagasse
Extractor rubber and resin removal efficiency	0.99	kg out with miscella/kg in
230: Bagasse Extraction		
Liquids left on bagasse after desolventizer	0.002	kg liquid/kg bagasse
240: Rubber Precipitation		
Solvent coagulation ratio	1	kg acetone/kg hexane
Liquids left on rubber after screw press	0.002	kg liquid/kg rubber
250: Resin Extraction		
Resin distillation efficiency	0.995	kg/kg
Water to acetone ratio in acetone scrubber	12	kg water/kg acetone
Acetone scrubbing efficiency	0.995	kg out/kg in
Hexane left in acetone leaving scrubber	0.01	kg out/kg in
Acetone distillation efficiency	0.995	kg out/kg in
Mineral oil to hexane ratio in hexane absorber	25	kg mineral oil/kg hexane
Hexane stripper efficiency	0.995	kg out/kg in
Mineral oil recovery efficiency	0.9999	kg recovered/kg in

Figure A.1. *Process model diagram of guayule rubber extraction facility*

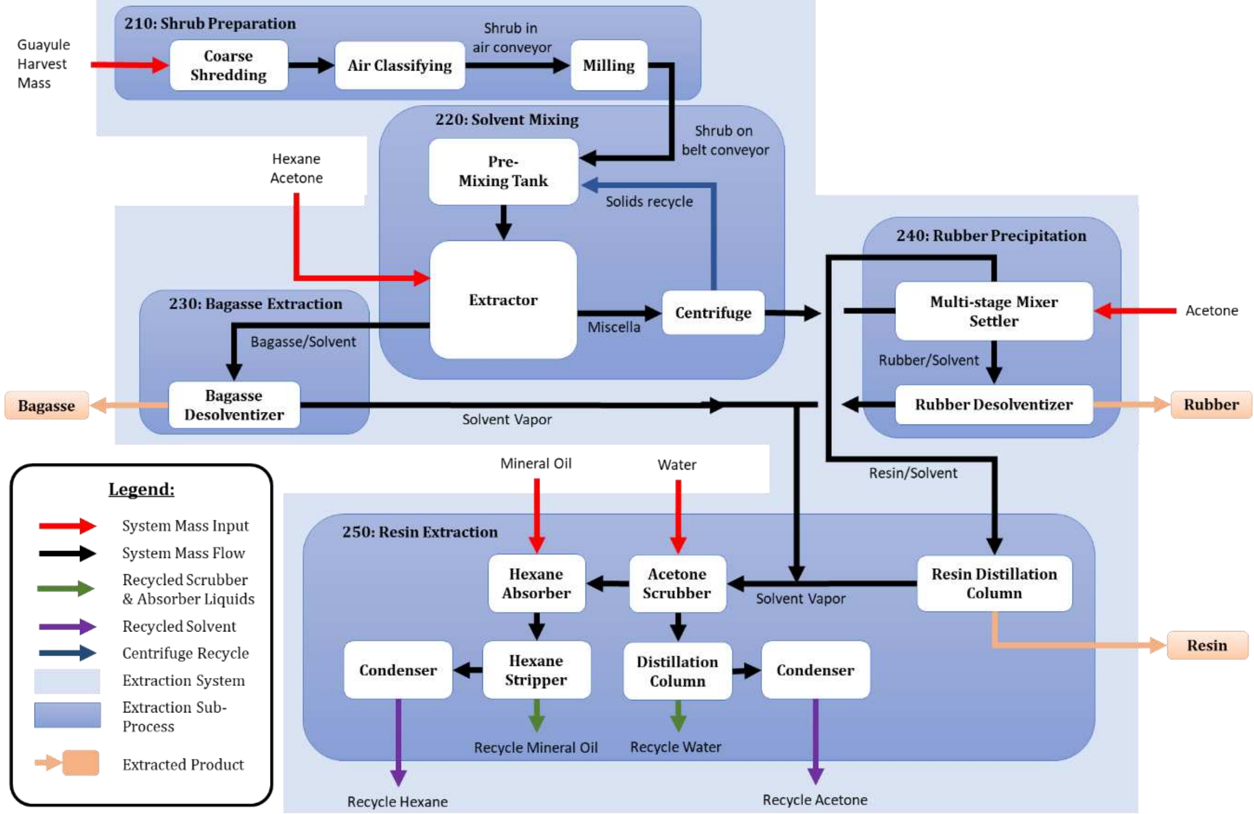
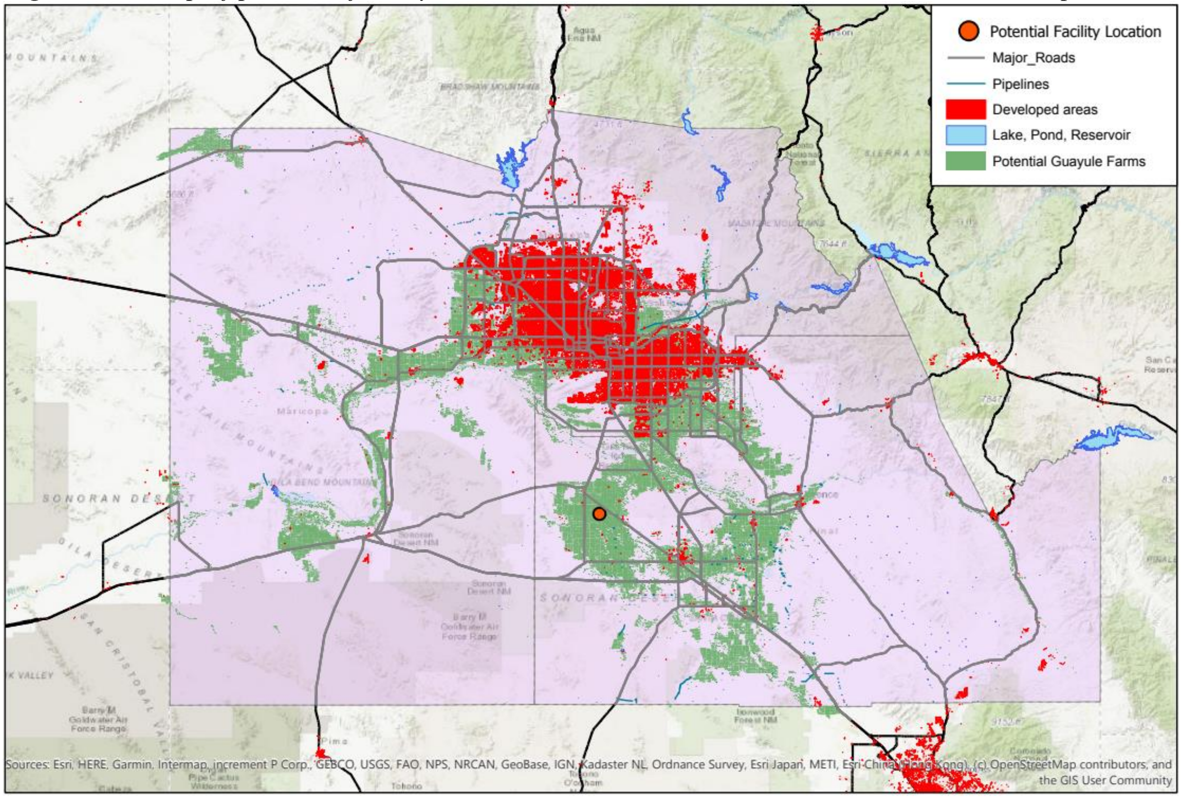


Figure A.2. *Map of potential facility location and associated data used to determine transport distance.*



Data sources for agricultural process and economic modeling:

The original model was developed based on traditional commodity cropping systems for Maricopa County, Arizona. A list of power units, equipment, and field operations[126] for cotton, field corn, sorghum, wheat and alfalfa was included. The purchase price, useful life, power unit fuel use[127] and speed, equipment width, field efficiency, and times each field operation occurred during a production cycle were also include for power units and equipment[126]. From this information, total hours of use, fuel and lube requirements[127], repair and maintenance costs[128], and depreciation or replacement costs[129] for power units and equipment were calculated on an annual and per acre basis. Production inputs, fuel, labor, and irrigation water costs, as well as an interest rate for operating lines of credit generated cash-based enterprise budgets for each crop. However, inputs used and applied were based on past prices paid and received by producers. Yields and prices were updated interviewing producers, industry experts, and machinery dealers[130]; commodity prices received by the producer were also modified[131]. The costs to establish and produce guayule were incorporated into the model based on information from prior research and cooperating producers. Enterprise budgets for each of these crops were combined with other crops for a whole farm integrated model.

Table A.4. *Guayule agriculture costs in first year of six-year growth cycle.*

Guayule Establishment Year				
Non-Harvest Production Inputs and Machine Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
Seed	---	---	---	$7,503
Fertilizer - N2	Pound	0.25	18525.00	$4,631
Fertilizer - P	Pound	0.21	37050.00	$7,781
Herbicide Prowl	Pint	6.50	1667.25	$10,837
Herbicide Aim	Ounce	5.62	333.45	$1,874
Herbicide Fusilade	Ounce	1.09	3705.00	$4,038
Irrigation Water (Flood)	/AC FT	60.00	741.00	$44,460
Irrigation Labor (Flood)	Hour	13.13	138.94	$1,824
175 HP Tractor & V-Ripper (Repairs, maint., fuel & lube)	Acre	13.79	185.25	$2,555
175 HP Tractor & V-Ripper (Labor)	Acre	5.84	185.25	$1,082
175 HP Tractor & 18' Disc (Repairs, maint., fuel & lube)	Acre	4.72	370.50	$1,749
175 HP Tractor & 18' Disc (Labor)	Acre	1.65	370.50	$613
175 HP Tractor & Landplane (Repairs, maint., fuel & lube)	Acre	6.93	185.25	$1,284
175 HP Tractor & Landplane (Labor)	Acre	2.92	185.25	$541
125 HP Tractor & Fertilizer Spreader (Repairs, maint., fuel & lube)	Acre	2.85	185.25	$527
125 HP Tractor & Fertilizer Spreader (Labor)	Acre	1.42	185.25	$263
175 HP Tractor & 4-Row Lister (Repairs, maint., fuel & lube)	Acre	7.89	185.25	$1,461
175 HP Tractor & 4-Row Lister (Labor)	Acre	3.72	185.25	$690
125 HP Tractor & Boom Sprayer (Repairs, maint., fuel & lube)	Acre	1.84	185.25	$340
125 HP Tractor & Boom Sprayer (Labor)	Acre	1.22	185.25	$226
175 HP Tractor & Bed Shaper (Repairs, maint., fuel & lube)	Acre	4.76	185.25	$882
175 HP Tractor & Bed Shaper (Labor)	Acre	2.00	185.25	$371
175 HP Tractor & 8-Row Planter (Repairs, maint., fuel & lube)	Acre	4.62	185.25	$856
175 HP Tractor & 8-Row Planter (Labor)	Acre	1.67	185.25	$309
125 HP Tractor & 8-Row Rolling Cultivator (Repairs, maint., fuel & lube)	Acre	2.03	370.50	$752
125 HP Tractor & 8-Row Rolling Cultivator (Labor)	Acre	1.49	370.50	$552
Property insurance	Acre	0.85	185.25	$157
Property taxes	Acre	2.43	185.25	$450
Other Expenses	Percent		5%	$4,930
Interest on Operating Capital			4%	$4,142
Total Non-Harvest Production Inputs and Machine Costs				**$107,681**
Replacement Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
175 HP Tractor & V-Ripper	Acre	5.20	185.25	$963
175 HP Tractor & 18' Offset Disc	Acre	3.72	370.50	$1,379
175 HP Tractor & Landplane	Acre	32.99	185.25	$6,112
125 HP Tractor & Fertilizer Spreader	Acre	1.88	185.25	$348
175 HP Tractor & 4-Row Lister	Acre	4.15	185.25	$769
125 HP Tractor & Boom Sprayer	Acre	1.31	185.25	$243
175 HP Tractor & Bed Shaper	Acre	5.33	185.25	$987
175 HP Tractor & 8-Row Planter	Acre	10.75	185.25	$1,992
Saddle Tank Sprayer attached to Planter	Acre	1.11	370.50	$411
125 HP Tractor & 8-Row Rolling Cultivator	Acre	2.71	370.50	$1,006
Total Replacement Costs				**$14,210**
Total Annual Costs				**$121,891**

Table A.5. *Guayule agriculture costs in third and fifth year of six year growth cycle.*

Guayule Growing Year

Non-Harvest Production Inputs and Machine Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
Fertilizer - N2	Pound	0.25	18525.00	$4,631
Fertilizer - P	Pound	0.21	37050.00	$7,781
Herbicide Prowl	Pint	6.50	1667.25	$10,837
Herbicide Aim	Ounce	5.62	333.45	$1,874
Herbicide Fusilade	Ounce	1.09	3705.00	$4,038
Irrigation Water (Flood)	/AC FT	60	741.00	$44,460
Irrigation Labor (Flood)	Hour	13.13	138.94	$1,824
125 HP Tractor & 8-Row Rolling Cultivator (Repairs, maint., fuel & lube)	Acre	2.03	185.25	$376
125 HP Tractor & 8-Row Rolling Cultivator (Labor)	Acre	1.49	185.25	$276
Property insurance	Acre	0.85	185.25	$157
Property taxes	Acre	2.43	185.25	$450
Other Expenses			5%	$3,835
Interest on Operating Capital			4%	$3,222
Total Non-Harvest Production Inputs and Machine Costs				**$83,762**
Replacement Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
125 HP Tractor & 8-Row Rolling Cultivator	Acre	2.71	185.25	$503
Total Replacement Costs				**$503**
Total Annual Costs				**$84,265**

Table A.6. *Guayule agriculture costs in second, fourth, and sixth year of six year growth cycle.*

Guayule Harvest Year				
Harvest Inputs and Machine Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
Swathing (Repairs, maint., fuel & lube)	Acre	16.40	185.25	$ 3,038
Swathing (Labor)	Acre	15.27	185.25	$ 2,829
125 HP Tractor & Baler (Repairs, maint., fuel & lube)	Acre	20.74	185.25	$ 3,841
125 HP Tractor & Baler (Labor)	Acre	15.27	185.25	$ 2,829
Bale Wagon (Repairs, maint., fuel & lube)	Acre	2.78	185.25	$ 515
Bale Wagon (Labor)	Acre	2.48	185.25	$ 460
Interest on Harvest Operating Capital			4%	$ 541
Total Harvest Inputs and Machine Costs				**$ 14,054**
Non-Harvest Production Inputs and Machine Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
Fertilizer - N2	Pound	0.25	18,525.00	$ 4,631
Fertilizer - P	Pound	0.21	37,050.00	$ 7,781
Herbicide Prowl	Pint	6.50	1,667.25	$ 10,837
Herbicide Aim	Ounce	5.62	333.45	$ 1,874
Herbicide Fusilade	Ounce	1.09	3,705.00	$ 4,038
Irrigation Water (Flood)	/AC FT	60	741.00	$ 44,460
Irrigation Labor Flood)	Hour	13.13	138.94	$ 1,824
175 HP Tractor & 18' Disc (Repairs, maint., fuel & lube)	Acre	4.72	37.05	$ 175
175 HP Tractor & 18' Disc (Labor)	Acre	1.65	37.05	$ 61
125 HP Tractor & 8-Row Rolling Cultivator (Repairs, maint., fuel & lube)	Acre	2.03	185.25	$ 376
125 HP Tractor & 8-Row Rolling Cultivator (Labor)	Acre	1.49	185.25	$ 276
Property insurance	Acre	0.85	185.25	$ 157
Property taxes	Acre	2.43	185.25	$ 450
Other Expenses			5%	$ 3,847
Interest on Operating Capital			4%	$ 3,232
Total Non-Harvest Production Inputs and Machine Costs				**$ 84,020**
Replacement Costs	**Unit**	**$/Unit**	**Quantity**	**Value**
Swathing	Acre	93.53	185.25	$17,327
125 HP Tractor & Baler	Acre	186.79	185.25	$34,604
Bale Wagon	Acre	0.20	185.25	$37
175 HP Tractor & 18' Offset Disc	Acre	3.72	37.05	$138
125 HP Tractor & 8-Row Rolling Cultivator	Acre	2.71	185.25	$503
Total Replacement Costs				**$52,608**
Total Annual Costs				**$150,682**

Table A.7. *Guayule rubber extraction facility capital costs.*

Total Capital Costs			**$**	**271,354,530**
Land and Buildings (Materials and construction)			**$**	**6,700,952**
Land (acres)	10	acres	$	22,763
Processing Structure	9,290	m^2	$	2,200,000
Office	2,322	m^2	$	3,973,750
Guayule Storage	5,125	m^2	$	504,439
Equipment (Purchase and Install)			**$**	**259,928,578**
Shredder	1	units	$	366,247
Air Conveyor	1	units	$	73,096
Air Classifyer	1	units	$	73,096
Hammer Mill	1	units	$	366,247
Belt Conveyor	1	units	$	10,875,280
Solvent Pump	1	units	$	284,740
Vertical Mixing Tank	3	units	$	1,848,327
Slurry Pump	1	units	$	1,088,930
CC Extractor	1	units	$	1,375,418
Centrifuge	1	units	$	8,671,403
Tray Dryer	1	units	$	13,130,032
Mixer Settler	1	units	$	1,375,418
Heated Screw Press	1	units	$	6,854,400
Mineral Oil Pump	3	units	$	472,685
Water Pump	2	units	$	157,562
Resin Distillation Column	1	units	$	13,153,889
Hexane Recovery Equipment	1	units	$	109,057,119
Hexane Condenser	1	units	$	61,666
Acetone Recovery Equipment	1	units	$	90,611,533
Acetone Condenser	1	units	$	31,491
Transport of Biomass			**$**	**4,725,000**
Truck (15 year life)	28	units	$	4,725,000

Table A.8. *Guayule rubber extraction facility operational costs*

Total Annual Operational Costs			**$ 121,151,005**
Variable Operating Costs			**$ 102,274,800**
Electricity	433,813,559	MJ	$ 7,799,494
Natural Gas	2,488,831,750	MJ	$ 12,775,059
Acetone	14,207	metric tons	$ 8,610,639
Hexane	23,790	metric tons	$ 11,289,245
Water	55,454	metric tons	$ 5,313
Mineral Oil	2,484	metric tons	$ 4,222,166
Guayule Biomass	500,000	metric tons	$ 57,572,884
Transport of Biomass	500,000	metric tons	$ 559,788
Fixed Operating Costs			**$ 18,316,417**
Manager	1	employees	$ 185,398
Engineer	1	employees	$ 89,597
Maintenance Supervisor	1	employees	$ 71,908
Maintenance Technician	16	employees	$ 806,837
Laboratory Manager	1	employees	$ 70,644
Laboratory Technician	3	employees	$ 151,282
Shift Operators	40	employees	$ 2,421,429
Yard Employees	12	employees	$ 423,176
Clerks or Secretary	3	employees	$ 136,119
Benefits	90%	of salary	$ 3,920,751
Maintenance	3%	of capital investment	$ 8,139,953
Insurance	1%	of capital investment	$ 1,899,322

Table A.9. *Guayule solvent extraction processing facility on-site heat and power parameters and costs*

On-Site Heat and Power Parameters		
Bagasse higher heating value	18.3	MJ/kg
System wide bagasse heating efficiency	0.7	MJ heat/MJ combusted
System wide bagasse electricity efficiency	0.2	MJ electricity/MJ combusted
Capital cost	$ 1,300	per kW
Maintenance	3	%
Labor	8	operators
Electricity sale	$ 0.05	per kWh

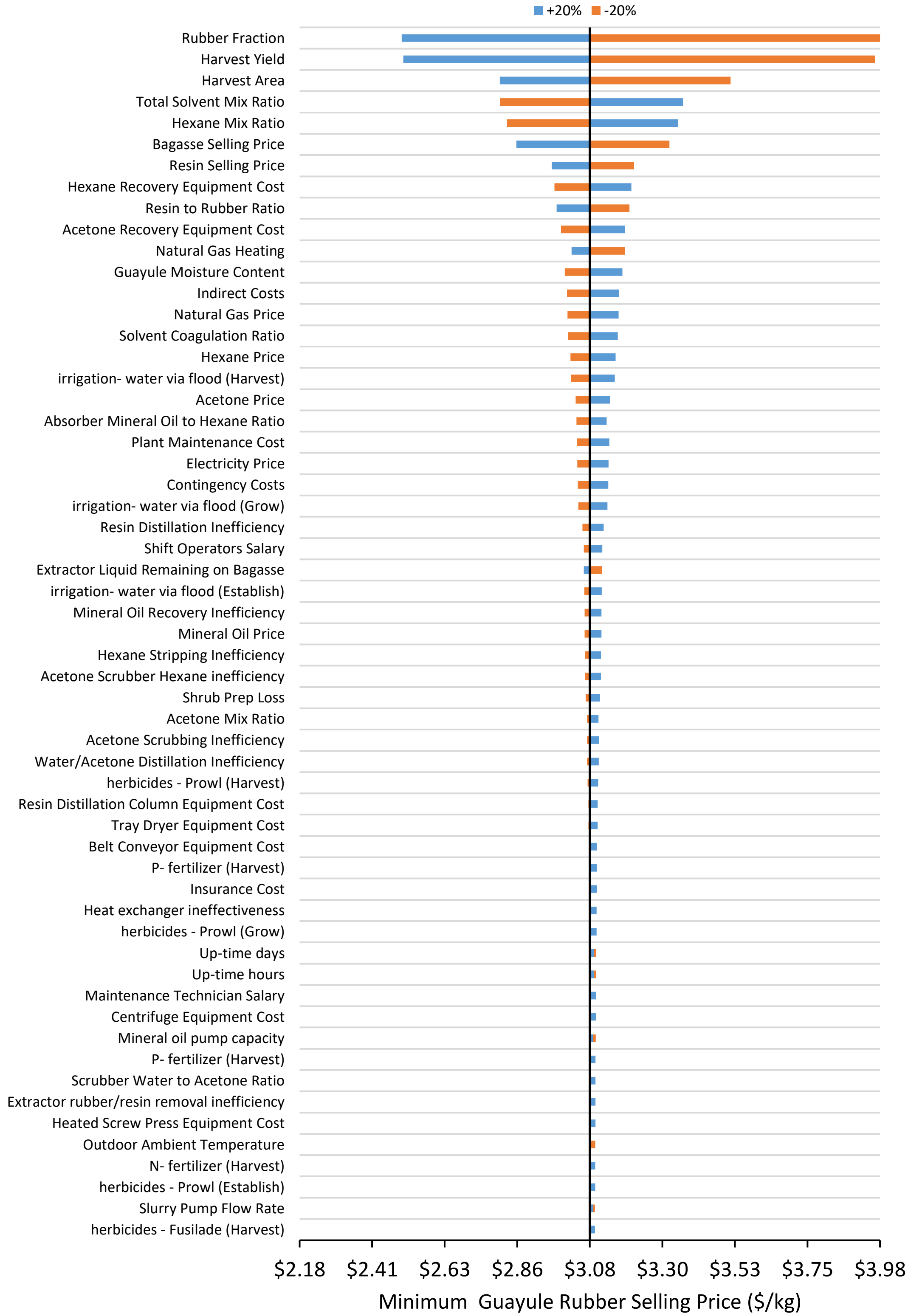
Table A.10. *Life cycle inventory data sources used for environmental impact analysis.*

Process	Source
Diesel	ecoinvent - diesel production, low-sulfer | diesel, low-sulfer | Cutoff, S - RoW USLCI - Diesel, combusted in industrial equipment
Shed, construction	ecoinvent - shed construction | shed | Cutoff, S - RoW
Tractor, production	ecoinvent - tractor production, 4-wheel, agricultural | tractor, 4-wheel, agricultural | Cutoff, S - RoW
Agricultural Machinery, tillage, production	ecoinvent - agricultural machinery production, tillage | agricultural machinery, tillage | Cutoff, S - RoW
Agricultural Machinery, unspecified, production	ecoinvent - agricultural machinery production, unspecified | agricultural machinery, unspecified | Cutoff, S - RoW
Electricity supply	ecoinvent - electricity, high voltage, production mix | electricity, high voltage | Cutoff, S - WECC, US only
Harvester production	ecoinvent - harvester production | harvester | Cutoff, S - RoW
Polyethylene production, high density, granulate	ecoinvent - polyethylene production, high density, granulate | polyethylene, high density, granulate | Cutoff, S - RoW
Extrusion plastic film production	ecoinvent - extrusion production, plastic film | extrusion, plastic film | Cutoff, S - RoW
Excavation hydraulic digger production	ecoinvent - excavation, hydraulic digger | excavation, hydraulic digger | Cutoff, S - RoW
Cast iron production	cast iron production | cast iron | Cutoff, S
Polyvinylchloride production	ecoinvent - polyvinylchloride production, bulk polymerisation | polyvinylchloride, bulk polymerised | Cutoff, S - RoW
Water supply	ecoinvent - tap water production, direct filtration treatment | tap water | Cutoff, S - RoW
Natural gas production	ecoinvent - natural gas processing plant production | natural gas processing plant | Cutoff, S USLCI - Natural gas, combusted in industrial equipment
Isohexane production	ecoinvent - isohexane production, isohexane - Cutoff - RoW
Cyclohexane production	ecoInvent - cyclohexane production, cyclohexane - Cutoff - RoW
Acetone production	ecoInvent - acetone production, liquid | acetone, liquid | Cutoff, S
Mineral oil production	USLCI - white mineral oil at plant
Triple Superphosphate Production	triple superphosphate production | phosphate fertiliser, as P2O5 | Cutoff, S - RoW
Urea Production	urea production, as N | urea, as N | Cutoff, S - RoW
Trailer Production	ecoinvent - agricultural trailer production | agricultural trailer | Cutoff, S - RoW
Ammonium Nitrate Production	ammonium nitrate production | ammonium nitrate, as N | Cutoff, S
Pendimethalin Production	ecoinvent - pendimethalin production | pendimethalin | Cutoff, S - RoW
Transport by Truck	USLCI - Transport, combination truck, short-haul, diesel powered, Southwest
Combustion of wood waste	USLCI - Wood waste, unspecified, combusted in industrial boiler ***Global Warming set to 0 for bagasse

Table A.11. *Life cycle inventory data used for environmental impact analysis.*

		Acidification	Ecotoxicity	Eutrophication	Global Warming	Human Health - carcinogenics	Human Health - non-carcinogenics	Ozone Depletion	Photochemical ozone formation	Resource depletion - fossil fuels	Respiratory effects
Process	Functional Unit	kg SO2 eq	CTUe	kg N eq	kg CO2 eq	CTUh	CTUh	kg CFC-11 eq	kg O3 eq	MJ surplus	kg PM2.5 eq
Diesel	kg	4.90E-02	8.83E-01	4.53E-03	3.78E+00	1.70E-08	3.64E-08	9.14E-07	1.59E+00	7.62E+00	1.43E-03
Shed, construction	m^2	9.98E-01	2.55E+03	8.00E-01	3.33E+02	3.53E-05	1.13E-04	1.74E-05	1.51E+01	1.71E+02	1.76E-01
Tractor,	kg	4.37E-02	9.71E+01	4.06E-02	8.19E+00	1.01E-06	4.59E-06	7.28E-07	3.75E-01	8.56E+00	8.81E-03
Agricultural Machinery, tillage,	kg	3.06E-02	4.82E+01	2.53E-02	6.67E+00	1.13E-06	1.56E-06	3.59E-07	3.09E-01	3.61E+00	8.20E-03
Agricultural Machinery,	kg	2.65E-02	4.13E+01	2.25E-02	5.78E+00	9.43E-07	1.46E-06	3.37E-07	2.68E-01	3.46E+00	6.77E-03
Electricity supply	kWh	1.14E-03	2.81E+00	3.74E-03	4.95E-01	3.92E-08	1.11E-07	3.73E-08	1.60E-02	4.02E-01	1.36E-03
Harvester	kg	3.96E-02	9.90E+01	3.85E-02	6.92E+00	1.13E-06	4.57E-06	4.28E-07	3.42E-01	5.05E+00	8.25E-03
Polyethylene production, high density, granulate	kg	6.43E-03	1.16E+00	4.76E-04	1.94E+00	6.23E-08	2.43E-08	1.22E-09	8.15E-02	9.45E+00	4.43E-04
Extrusion plastic film production	kg	3.03E-03	2.25E+00	2.35E-03	7.04E-01	3.47E-08	9.94E-08	3.67E-08	3.36E-02	5.14E-01	9.15E-04
Excavation hydraulic digger	m^3	5.08E-03	7.32E-01	7.06E-04	5.39E-01	2.45E-08	2.35E-08	1.25E-07	1.51E-01	1.06E+00	7.06E-04
Cast iron	kg	8.02E-03	3.38E+01	5.69E-03	1.85E+00	2.78E-06	3.67E-07	1.16E-07	9.99E-02	1.03E+00	2.43E-03
Polyvinylchloride production	kg	6.10E-03	2.90E+00	1.21E-03	2.07E+00	1.30E-07	6.93E-08	1.89E-08	1.09E-01	6.06E+00	3.91E-04
Water supply	kg	1.13E-06	8.13E-04	8.92E-07	2.56E-04	1.40E-11	3.76E-11	1.47E-11	1.27E-05	1.58E-04	3.72E-07
Natural gas production	kg	4.35E-03	1.40E+00	1.02E-03	3.06E+00	2.01E-08	4.70E-08	3.67E-07	7.90E-02	7.26E+00	4.18E-04
Isohexane	kg	6.11E-03	6.47E+00	5.90E-03	9.61E-01	5.06E-08	2.91E-07	7.09E-07	5.87E-02	6.04E+00	7.53E-04
Cyclohexane production	kg	1.13E-02	9.20E+00	7.91E-03	2.60E+00	1.31E-07	3.83E-07	1.53E-07	1.13E-01	8.00E+00	2.62E-03
Acetone	kg	1.02E-02	8.75E-01	1.45E-03	2.23E+00	4.56E-08	1.86E-08	1.00E-09	1.15E-01	8.56E+00	6.05E-04
Mineral oil	kg	0.00E+00	9.11E-03	0.00E+00	0.00E+00	9.26E-10	2.18E-12	0.00E+00	1.48E-04	0.00E+00	0.00E+00
Triple Superphosphate	kg	2.09E-02	2.21E+01	2.75E-02	1.94E+00	1.41E-07	1.18E-06	2.30E-07	1.46E-01	3.17E+00	3.59E-03
Urea Production	kg	1.81E-02	1.21E+01	5.88E-03	3.34E+00	9.27E-08	5.63E-07	5.84E-07	1.07E-01	7.53E+00	3.03E-03
Trailer Production	kg	4.16E-02	4.35E+01	2.66E-02	7.95E+00	1.38E-06	1.78E-06	4.23E-07	3.99E-01	4.70E+00	8.73E-03
Ammonium Nitrate Production	kg	3.66E-02	2.56E+01	1.67E-02	8.80E+00	1.48E-07	1.23E-06	5.79E-07	3.90E-01	7.07E+00	3.38E-03
Pendimethalin Production	kg	2.30E-02	1.69E+01	1.92E-02	5.87E+00	1.57E-07	7.96E-07	3.11E-07	2.52E-01	9.55E+00	2.68E-03
Transport by Truck	ton-km	4.64E-04	0.00E+00	2.93E-05	9.09E-02	0.00E+00	0.00E+00	0.00E+00	1.59E-02	0.00E+00	3.93E-05
Combustion of wood waste	kg	1.62E-03	6.78E-03	9.68E-04	1.76E+00	4.37E-07	2.64E-08	2.96E-07	5.32E-02	0.00E+00	1.04E-03

Figure A.2. *±20% economic sensitivity analysis results for all variables that change minimum selling price of guayule rubber in the baseline scenario by more than $0.01 per kg of rubber.*



Derivation of global warming values for synthetic and hevea rubber in Table 2.2:

The global warming for SBR is a mean estimate of three sources varying from 2.7-3.6 kg CO_2-eq per kg of rubber[25,39,46]. Determining greenhouse gases of Hevea rubber production was a bit more challenging as typical Hevea results are based on foreign production only and do not include transport to the United States. Overcoming this limitation required estimating a sea transport distance of 14,358 km (Bangkok to Los Angeles) and a truck transport distance of 1000 km. These distance estimates were combined with life cycle data from ecoinvent 3.4[39] resulting in a transportation impact of 0.25 kg CO_2-eq per kg of rubber. This transportation impact was added to a published production value of 0.66 kg CO_2-eq per kg of RSS3 produced in Thailand[47], yielding total emissions of 0.91 kg CO_2-eq per kg hevea rubber shown in Table 2.2 of the main text.

APPENDIX B

Repository of Terms in Equations 3.1-3.4

Dynamic Global Warming Impact (DGWI) - Ratio of monetized impact of a greenhouse gas (GHG) emission in a given year (i) to monetized impact of an equivalent CO_2 emission in the present year (2020). Expressed as a unitless ratio.

$Emissions_{GHG,i}$ - The mass of a greenhouse gas (GHG) emitted in a given year (i). Expressed in unit of grams of GHG.

Emissions Based Operational $Costs_{GHG,i}$ - The total monetized social cost of greenhouse gas (GHG) emissions in a given year (i). Expressed in units of 2020 U.S. dollars.

Mean Present Value - The present values of CO_2, CH_4, and N_2O emissions summed over each year of operation (i) and divided by the energy generated in each year, until end of life (n). Expressed in unit of grams CO2-eq per kWh.

Present $Value_{GHG,i}$ - The mass of a greenhouse gas (GHG) emitted in a given year (i) weighted by its monetized impact compared to an equivalent emission of CO_2 in the present year (2020). Expressed in unit of grams of CO_2-eq.

Social $Cost_{GHG,i}$ - The estimated social cost of a greenhouse gas (GHG) emitted in a given year (i). Expressed in unit of 2020 U.S. dollars

Derivation of Temporally Resolved Greenhouse Gas Emissions

As discussed in the introduction of the main text, the majority of LCA report a single value of equivalent carbon emissions resulting from electricity generation (gCO_2-eq/kWh). This single value represents the average emissions across the lifetime of a technology after application of the global warming potential (GWP). This presented two challenges when applying the new methodology. First, emissions needed to be allocated to the construction phase (occurring in the first year) and operational phase (occurring over the full lifetime). Second, the specific CO_2, CH_4, and N_2O emissions occurring in each phase needed to be estimated. These challenges were addressed by locating existing literature that presents results for each gas within the two phases. Details of references are presented in the sections below. It is worth noting that these references may limit the quality of data when compared to large-scale harmonized reviews. However, most harmonized reviews do not present detailed accounting for each lifetime phase or individual greenhouse gas. In an attempt to validate the references, the standard LCA results of this research phase have been compared to harmonized literature reviews[82–84,132–134] in Figure B.1. Across all technologies the standard LCA estimates are within the range of harmonized reported values.

Coal with and without Carbon Capture and Sequestration (CCS): A National Energy Technology Laboratory (NETL) report contains CO_2, CH_4, and N_2O emissions associated with construction and operation across coal acquisition, transport, and conversion to electricity[76]. In addition, the report considers CCS that captures 90% of CO_2 combustion emissions for baseline calculations.

Natural Gas with and without CCS: An NETL report contains CO_2, CH_4, and N_2O emissions associated with construction and operation across acquisition, transportation, and combustion of natural gas[77]. This analysis considered a natural gas combined cycle (NGCC) power plant using domestic onshore natural gas. Fugitive methane emissions were updated to reflect the most recent and comprehensive estimates[78].

Similar to coal, CCS for natural gas was considered to sequester 90% of CO_2 combustion emissions for baseline calculations.

Photovoltaic (PV): Ravikumar provides breakouts of CO_2, CH_4, and N_2O emissions for PV panel manufacturing on a peak power (g/kWp) basis[63]. This analysis utilized the manufacturing emissions associated with a polycrystalline silicon panel. Using a capacity factor of 22%, g/kWp was translated to g/kWh. These emissions were combined with operational emissions provided by Hou for distributed PV panels[79]. As stated in the main text, there was no accounting for CH_4 and N_2O emissions within the operational phase as the contributions of these gases are considered negligible.

Concentrated Solar Power (CSP): An NETL report contains CO_2, CH_4, and N_2O emissions for collector construction, plant construction, and plant operation[80]. As stated in the main text, there was no attempt to account for CH_4 and N_2O emissions within the operational phase as the contributions of these gases are considered negligible.

Nuclear: An NETL report contains CO_2, CH_4, and N_2O for raw material acquisition, raw material transport, and the energy conversion facility[81]. Unlike other NETL reports, there is not a clear breakdown of construction and operational emissions. Based on the details of the report, the analysis did not include operational emissions within the energy conversion facility. As a result, the emissions in this stage are all associated with construction of the facility. The remaining emissions across raw material acquisition and transportation were considered operational emissions. This analysis considered existing nuclear power with centrifuge enrichment and no long-term waste management plan. As stated in the main text, no attempt was made to account for CH_4 and N_2O emissions within the operational phase as the contributions of these gases are considered negligible.

Wind: An NETL report contains detailed breakouts of CO_2, CH_4, and N_2O emissions for wind power[80]. These emissions include construction of the wind farm and electrical infrastructure, as well as operation of the wind farm. This analysis considered onshore conventional wind power using domestically manufactured turbines. As stated in the main text, there was no attempt to account for CH_4 and N_2O emissions within the operational phase as the contributions of these gases are considered negligible.

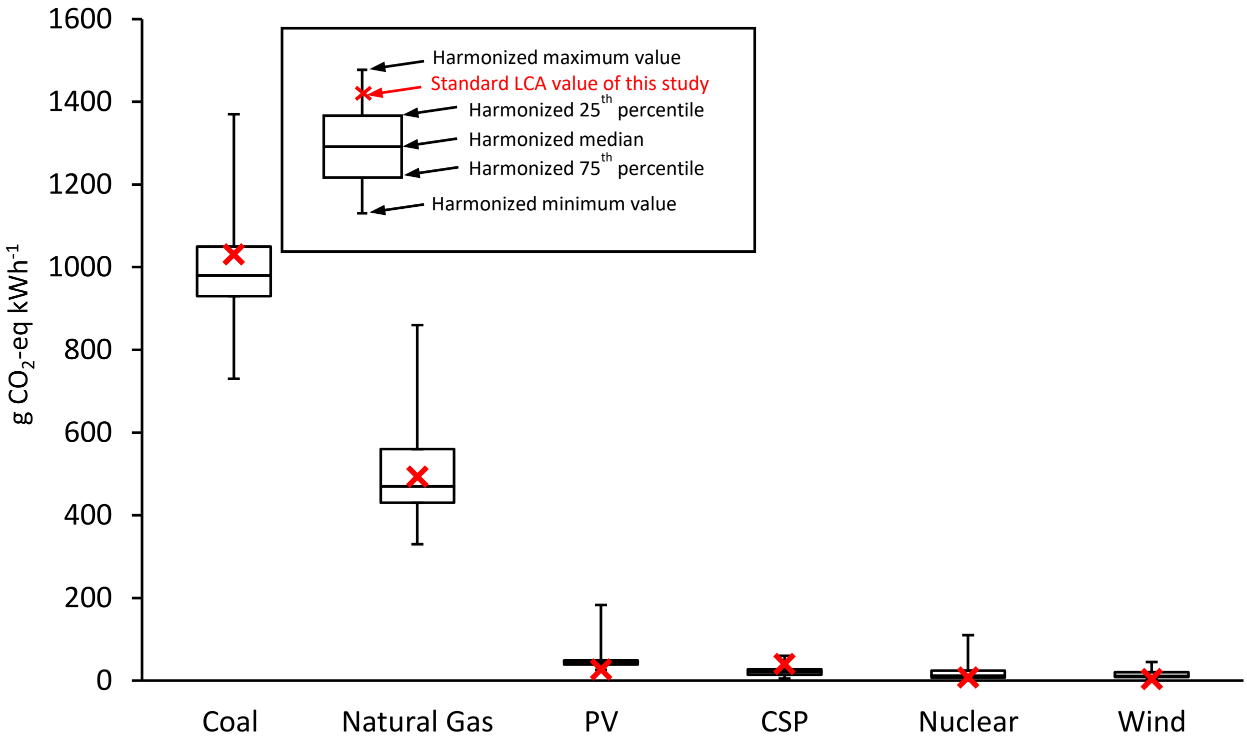


Figure B.1. *Standard LCA values used in this study (red x) compared to results of harmonized literature reviews for each technology*[82–84,132–134].

Temporally Resolved Coal CCS Power Plant Emissions Profile

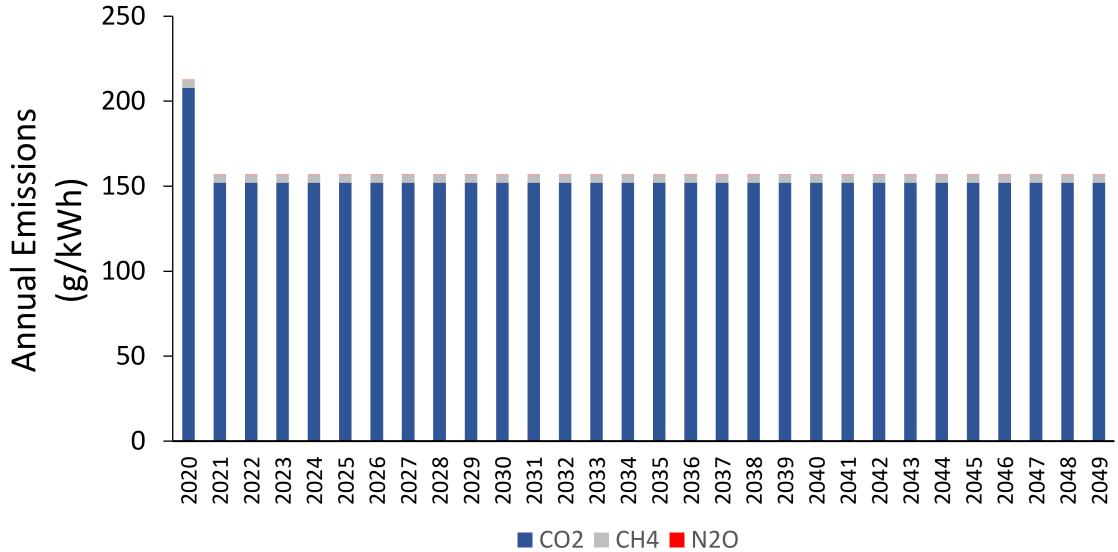


Figure B.2. *Temporally resolved emissions profile of coal power plant with CCS, including construction emissions (year 2020) and operational emissions (years 2020-2049).*

Selection of Techno-Economic Data

The analysis was built with techno-economic data from the National Renewable Energy Laboratory's (NREL) 2018 Annual Technology Baseline (ATB)[85]. This data includes capital and operational expenditures as well as a range of economic variables related to financing and taxes. All variables were based upon ATB's R&D financials assumption which reflects fundamental technology changes but excludes short-term market variations in pricing and interest rates. Tables B.1 and B.2 detail the options selected in an attempt to match the configurations used for LCA.

Table B.1. *Techno-economic data options from NREL 2018 ATB*[85].

Technology	NREL ATB Options Selected
Coal	Advanced supercritical with SO_2 and NOx controls, mid technical advancement, high capacity factor
Coal CCS	Advanced supercritical with SO_2 and NOx controls, mid technical advancement, high capacity factor
Natural Gas	Combined cycle, mid technical advancement, high capacity factor
Natural Gas CCS	Combined cycle, mid technical advancement, high capacity factor
PV	Single axis tracking, mid technical advancement, located in Los Angeles, CA
CSP	Power tower, mid technical advancement, 10 hour thermal energy storage, Class 3
Nuclear	Advanced nuclear, mid technical advancement
Wind	Land-based, mid technical advancement, TRG 5

Table B.2. *Economics of Energy Generation: TEA cash flow costs and parameters for energy generation technologies based on NREL 2018 Annual Technology Baseline*[85].

Economic Parameter	**Coal**	**Natural Gas**	**Coal CCS**	**Natural Gas CCS**	**PV**	**CSP**	**Nuclear**	**Wind**
Years of operation	30	30	30	30	30	30	30	30
Rate of return on equity	9%	9%	9%	9%	9%	12%	9%	9%
Debt financing portion	60%	60%	60%	60%	60%	54%	60%	60%
Debt interest rate	4%	4%	4%	4%	4%	4%	4%	4%
MACRS Depreciation (years)	20	15	20	15	5	5	15	5
Income tax rate	26%	26%	26%	26%	26%	26%	26%	26%
Loan Term (years)	10	10	10	10	10	10	10	10
Construction Duration (years)	6	3	6	3	1	3	6	3
Equity spent in year -5	10%	0%	10%	0%	0%	0%	10%	0%
Equity spent in year -4	20%	0%	20%	0%	0%	0%	20%	0%
Equity spent in year -3	20%	0%	20%	0%	0%	0%	20%	0%
Equity spent in year -2	20%	80%	20%	80%	0%	80%	20%	80%
Equity spent in year -1	20%	10%	20%	10%	0%	10%	20%	10%
Equity spent in year 0	10%	10%	10%	10%	100%	10%	10%	10%
Capital cost ($/kW)	3589	1026	5496	2120	951	6498	5649	1500
Variable O+M ($/kWh)	0.005	0.003	0.01	0.007	0	0.0035	0.002	0
Fuel Costs ($/kWh)	0.019	0.026	0.024	0.031	0	0	0.007	0
Fixed O+M ($/kW-yr)	33	10	80	33	8	67	99	50
Capacity factor	85%	87%	85%	87%	22%	56%	92%	43%

Social Cost of Greenhouse Gases and Dynamic Global Warming Potentials

Table B.3. *Social cost of one metric ton of greenhouse gas (2020 U.S. dollars) based on 2.5%, 3%, 5%, and 3%-95th percentile IAM discount rates for the years 2020-2050[74,75].*

Year of Emission	Social Cost of CO_2				Social Cost of CH_4				Social Cost of N_2O			
	5%	3%	2.50%	3%-95th	5%	3%	2.50%	3%-95th	5%	3%	2.50%	3%-95th
2020	23	62	85	181	1018	1762	2206	4699	8863	22028	30327	57273
2021	23	62	87	185	1056	1762	2206	4846	9240	22028	31706	58741
2022	25	63	88	189	1113	1909	2343	4993	9428	23497	31706	60210
2023	25	65	90	194	1150	1909	2343	5140	9805	23497	31706	61678
2024	25	66	91	198	1188	2056	2481	5287	10183	23497	33084	63147
2025	26	68	94	203	1226	2056	2481	5434	10371	24965	33084	64615
2026	26	69	95	207	1263	2056	2619	5580	10748	24965	34463	66084
2027	28	70	96	210	1320	2203	2619	5727	11125	24965	34463	67553
2028	28	72	98	214	1358	2203	2757	5874	11314	26434	35841	69021
2029	28	72	99	219	1395	2350	2757	6021	11691	26434	35841	70490
2030	30	73	101	223	1433	2350	2757	6168	11880	27902	37220	71958
2031	30	75	102	228	1490	2350	2895	6315	12257	27902	37220	73427
2032	32	76	103	232	1546	2497	2895	6608	12822	27902	38598	74895
2033	32	78	105	236	1603	2497	3033	6755	13200	29371	38598	76364
2034	34	79	106	241	1659	2643	3033	6902	13577	29371	39977	79301
2035	34	81	108	247	1697	2643	3171	7196	13954	30839	39977	80769
2036	36	82	109	251	1754	2790	3308	7343	14331	30839	41355	82238
2037	36	84	112	256	1810	2790	3308	7490	14708	30839	41355	83706
2038	38	85	113	260	1867	2937	3446	7636	15085	32308	42734	85175
2039	38	87	114	264	1886	2937	3446	7930	15462	32308	42734	86643
2040	40	88	116	269	1886	2937	3584	8077	15839	33776	44112	88112
2041	40	90	117	273	2074	3084	3584	8224	16217	33776	44112	89581
2042	41	90	119	278	2074	3084	3722	8371	16594	33776	45491	91049
2043	41	91	120	282	2074	3231	3722	8517	17159	35245	45491	93986
2044	43	93	121	285	2263	3231	3860	8664	17537	35245	46869	95455
2045	43	94	123	289	2263	3378	3860	8958	17914	36713	46869	96923
2046	45	95	124	294	2263	3378	3998	9105	18479	36713	48248	98392
2047	45	97	127	298	2451	3524	3998	9252	18856	38182	48248	99860
2048	47	98	128	303	2451	3524	4136	9399	18856	38182	49626	101329
2049	47	100	130	307	2451	3671	4136	9545	18856	38182	49626	104266
2050	49	101	131	311	2451	3671	4273	9839	20742	39650	51005	105734

Table B.4. *Dynamic global warming impact for CO_2, CH_4, and N_2O relative to CO_2 in the year 2020 based on 2.5%, 3%, 5%, and 3%-95th percentile IAM discount rates for the years 2020-2050.*

Year of Emission	DGWI of CO_2				DGWI of CH_4				DGWI of N_2O			
	5%	3%	2.50%	3%-95th	5%	3%	2.50%	3%-95th	5%	3%	2.50%	3%-95th
2020	1.00	1.00	1.00	1.00	45	29	26	26	392	357	355	317
2021	1.00	1.00	1.02	1.02	47	29	26	27	408	357	371	325
2022	1.08	1.02	1.03	1.05	49	31	27	28	417	381	371	333
2023	1.08	1.05	1.05	1.07	51	31	27	28	433	381	371	341
2024	1.08	1.07	1.06	1.10	53	33	29	29	450	381	387	350
2025	1.17	1.10	1.10	1.12	54	33	29	30	458	405	387	358
2026	1.17	1.12	1.11	1.15	56	33	31	31	475	405	403	366
2027	1.25	1.14	1.13	1.16	58	36	31	32	492	405	403	374
2028	1.25	1.17	1.15	1.19	60	36	32	33	500	429	419	382
2029	1.25	1.17	1.16	1.21	62	38	32	33	517	429	419	390
2030	1.33	1.19	1.18	1.24	63	38	32	34	525	452	435	398
2031	1.33	1.21	1.19	1.26	66	38	34	35	542	452	435	407
2032	1.42	1.24	1.21	1.28	68	40	34	37	567	452	452	415
2033	1.42	1.26	1.23	1.31	71	40	35	37	583	476	452	423
2034	1.50	1.29	1.24	1.33	73	43	35	38	600	476	468	439
2035	1.50	1.31	1.26	1.37	75	43	37	40	617	500	468	447
2036	1.58	1.33	1.27	1.39	78	45	39	41	633	500	484	455
2037	1.58	1.36	1.31	1.41	80	45	39	41	650	500	484	463
2038	1.67	1.38	1.32	1.44	83	48	40	42	667	524	500	472
2039	1.67	1.40	1.34	1.46	83	48	40	44	683	524	500	480
2040	1.75	1.43	1.35	1.49	83	48	42	45	700	548	516	488
2041	1.75	1.45	1.37	1.51	92	50	42	46	717	548	516	496
2042	1.83	1.45	1.39	1.54	92	50	44	46	733	548	532	504
2043	1.83	1.48	1.40	1.56	92	52	44	47	758	571	532	520
2044	1.92	1.50	1.42	1.58	100	52	45	48	775	571	548	528
2045	1.92	1.52	1.44	1.60	100	55	45	50	792	595	548	537
2046	2.00	1.55	1.45	1.63	100	55	47	50	817	595	565	545
2047	2.00	1.57	1.48	1.65	108	57	47	51	833	619	565	553
2048	2.08	1.60	1.50	1.67	108	57	48	52	833	619	581	561
2049	2.08	1.62	1.52	1.70	108	60	48	53	833	619	581	577
2050	2.17	1.64	1.53	1.72	108	60	50	54	917	643	597	585

APPENDIX C

Table C.1. Operational and economic parameters used within the techno-economic analysis based on the National Renewable Energy Laboratory 2019 Annual Technology Baseline

Input	NGCC	CCS Addition
Rate of return on equity	9%	9%
Debt financing portion	60%	60%
Debt interest rate	4%	4%
MACRs depreciation (years)	15	15
Income tax rate	26%	26%
Loan term (years)	10	10
Construction duration (years)	3	1
Equity spent in year -2	80%	0%
Equity spent in year -1	10%	0%
Equity spent in year 0	10%	100%
Working capital	0	0
Capital cost ($/kW)	1026	Varied in analysis
Non-Fuel variable O+M ($/kWh)	0.003	0.007
Fixed O+M ($/kW-yr)	10	33
Annual loan payment ($/kW-yr)	75	Varied in analysis
Decommissioning cost ($/kW)	20	20

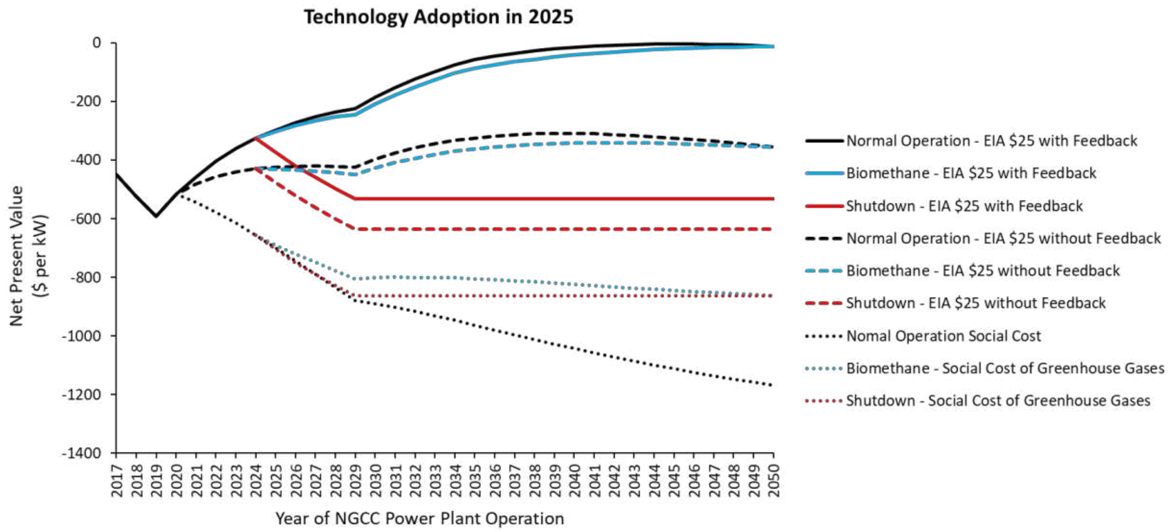


Figure C.1. *NPV of biomethane fuel switch, shutdown, and normal operation used to identify biomethane cost targets for a fuel switch in the year 2025.*

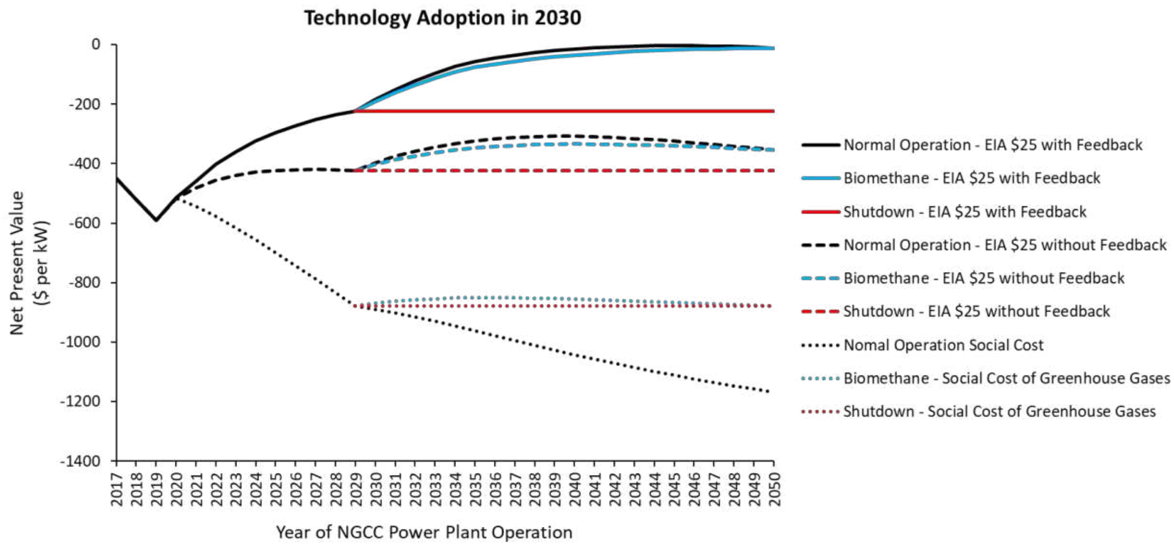


Figure C.2. *NPV of biomethane fuel switch, shutdown, and normal operation used to identify biomethane cost targets for a fuel switch in the year 2030.*

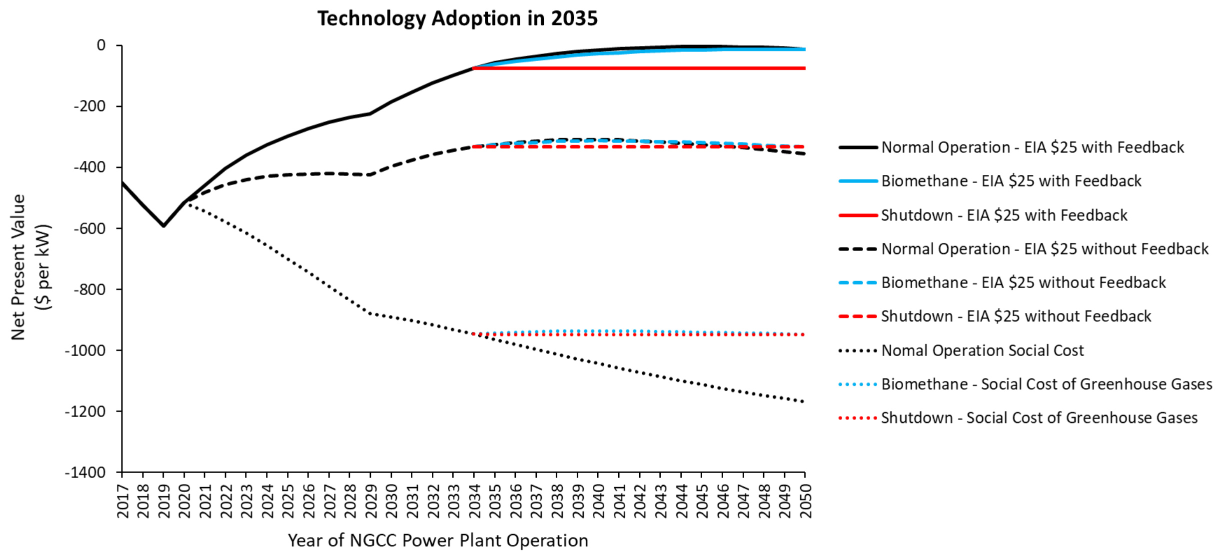


Figure C.3. *NPV of biomethane fuel switch, shutdown, and normal operation used to identify biomethane cost targets for a fuel switch in the year 2035.*

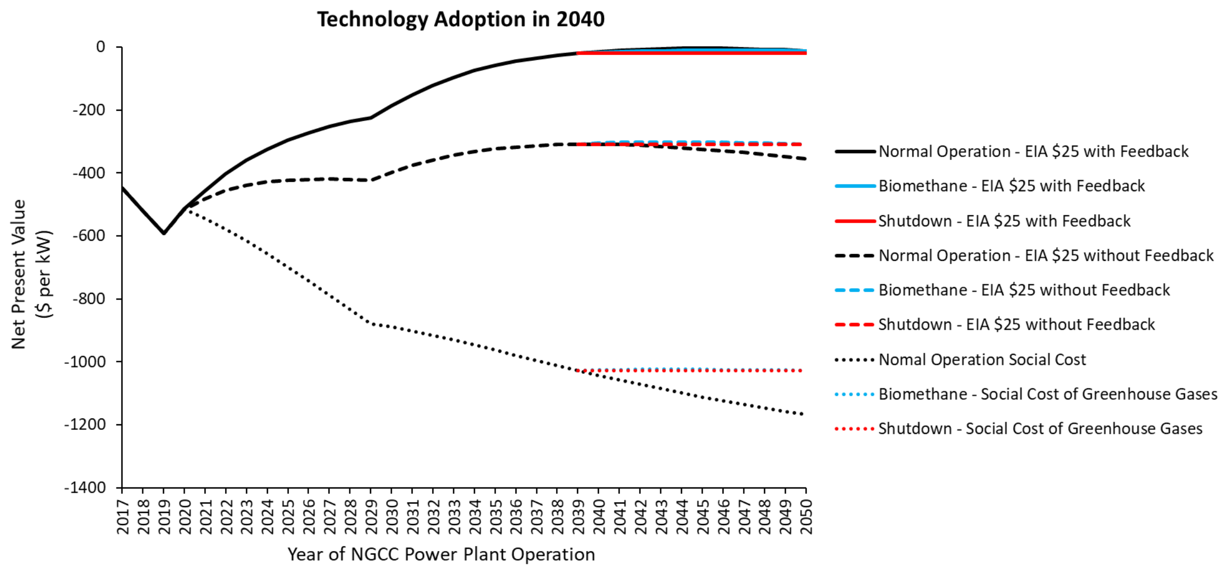


Figure C.4. *NPV of biomethane fuel switch, shutdown, and normal operation used to identify biomethane cost targets for a fuel switch in the year 2040.*

Table C.2. *Full list of cost targets for fuel switch to biomethane and addition of carbon capture and storage in 2025.*

2025		Fuel Cost ($ per mmBTU)										
		0	1	2	3	4	5	6	7	8	9	10
Emissions Pricing	**Heat Rate (mmBTU per MWh)**	**Capital Cost ($ per kW)**										
No Emissions Pricing	**6**	967	603	240	-100	-396	-694	-1040	-1420	-1800	-2180	-2561
	8	967	482	-2	-396	-801	-1293	-1800	-2307	-2814	-3321	-3828
	10	967	361	-199	-694	-1293	-1927	-2561	-3194	-3828	-4462	-5096
	12	967	240	-396	-1040	-1800	-2561	-3321	-4082	-4842	-5603	-6363
3% Social Cost	**6**	3124	2761	2398	2033	1667	1297	916	536	156	-224	-605
	8	2911	2426	1940	1450	944	437	-70	-577	-1084	-1591	-2098
	10	2697	2090	1478	845	212	-422	-1056	-1690	-2323	-2957	-3591
	12	2483	1752	1000	239	-521	-1282	-2042	-2802	-3563	-4323	-5084
EIA $25 without Feedback	**6**	1915	1554	1193	833	472	110	-263	-644	-1024	-1404	-1784
	8	1915	1434	953	472	-11	-517	-1024	-1531	-2038	-2545	-3052
	10	1915	1314	712	110	-517	-1151	-1784	-2418	-3052	-3686	-4319
	12	1915	1193	472	-263	-1024	-1784	-2545	-3305	-4066	-4826	-5587
EIA $25 with Feedback	**6**	1925	1565	1204	843	479	116	-202	-531	-911	-1291	-1672
	8	1925	1444	963	479	-4	-415	-911	-1418	-1925	-2432	-2939
	10	1925	1324	722	116	-415	-1038	-1672	-2305	-2939	-3573	-4206
	12	1925	1204	479	-202	-911	-1672	-2432	-3193	-3953	-4713	-5474

Table C.3. *Full list of cost targets for fuel switch to biomethane and addition of carbon capture and storage in 2030.*

2030		Fuel Cost ($ per mmBTU)										
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Emissions Pricing	**Heat Rate (mmBTU per MWh)**	**Capital Cost ($ per kW)**										
No Emissions Pricing	**6**	933	593	253	-71	-348	-625	-916	-1271	-1627	-1982	-2338
	8	933	480	26	-348	-719	-1152	-1627	-2101	-2576	-3050	-3525
	10	933	366	-163	-625	-1152	-1745	-2338	-2931	-3525	-4118	-4711
	12	933	253	-348	-916	-1627	-2338	-3050	-3762	-4473	-5185	-5897
3% Social Cost	**6**	2893	2550	2207	1858	1502	1146	790	435	79	-277	-633
	8	2678	2219	1751	1277	802	328	-147	-621	-1096	-1570	-2045
	10	2461	1882	1289	696	102	-491	-1084	-1677	-2270	-2863	-3456
	12	2245	1538	826	114	-597	-1309	-2021	-2733	-3444	-4156	-4868
EIA $25 without Feedback	**6**	1976	1637	1297	956	616	273	-81	-437	-793	-1149	-1505
	8	1976	1523	1070	616	156	-319	-793	-1267	-1742	-2216	-2691
	10	1976	1410	843	273	-319	-912	-1505	-2098	-2691	-3284	-3877
	12	1976	1297	616	-81	-793	-1505	-2216	-2928	-3640	-4352	-5063
EIA $25 with Feedback	**6**	1961	1623	1285	946	608	269	-58	-348	-696	-1052	-1408
	8	1961	1510	1059	608	156	-249	-696	-1170	-1645	-2119	-2594
	10	1961	1397	834	269	-249	-815	-1408	-2001	-2594	-3187	-3780
	12	1961	1285	608	-58	-696	-1408	-2119	-2831	-3543	-4254	-4966

Table C.4. *Full list of cost targets for fuel switch to biomethane and addition of carbon capture and storage in 2035.*

2035		Fuel Cost ($ per mmBTU)										
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Emissions Pricing	**Heat Rate (mmBTU per MWh)**	**Capital Cost ($ per kW)**										
No Emissions Pricing	**6**	859	555	250	-44	-292	-539	-790	-1073	-1391	-1709	-2028
	8	859	453	48	-292	-622	-969	-1391	-1815	-2240	-2664	-3089
	10	859	352	-126	-539	-969	-1497	-2028	-2558	-3089	-3619	-4150
	12	859	250	-292	-790	-1391	-2028	-2664	-3301	-3938	-4574	-5211
3% Social Cost	**6**	2582	2264	1945	1627	1309	990	672	354	35	-283	-601
	8	2368	1943	1519	1095	670	246	-179	-603	-1028	-1452	-1877
	10	2154	1623	1093	562	31	-499	-1030	-1560	-2091	-2621	-3152
	12	1939	1303	666	29	-607	-1244	-1881	-2517	-3154	-3791	-4427
EIA $25 without Feedback	**6**	1882	1577	1271	965	657	342	23	-295	-613	-932	-1250
	8	1882	1475	1067	657	236	-189	-613	-1038	-1462	-1887	-2311
	10	1882	1373	862	342	-189	-719	-1250	-1780	-2311	-2842	-3372
	12	1882	1271	657	23	-613	-1250	-1887	-2523	-3160	-3797	-4433
EIA $25 with Feedback	**6**	1945	1641	1337	1032	728	424	120	-150	-432	-751	-1069
	8	1945	1539	1134	728	323	-67	-432	-857	-1281	-1706	-2130
	10	1945	1438	931	424	-67	-538	-1069	-1600	-2130	-2661	-3191
	12	1945	1337	728	120	-432	-1069	-1706	-2342	-2979	-3616	-4252

Table C.5. *Full list of cost targets for fuel switch to biomethane and addition of carbon capture and storage in 2040.*

2040		Fuel Cost ($ per mmBTU)										
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Emissions Pricing	**Heat Rate (mmBTU per MWh)**	**Capital Cost ($ per kW)**										
No Emissions Pricing	**6**	693	453	212	-24	-227	-430	-633	-871	-1132	-1392	-1653
	8	693	372	51	-227	-498	-784	-1132	-1479	-1827	-2174	-2521
	10	693	292	-92	-430	-784	-1218	-1653	-2087	-2521	-2956	-3390
	12	693	212	-227	-633	-1132	-1653	-2174	-2695	-3216	-3738	-4259
3% Social Cost	**6**	2098	1838	1577	1316	1056	795	535	274	13	-247	-508
	8	1914	1566	1219	871	524	176	-171	-518	-866	-1213	-1561
	10	1730	1295	861	426	-8	-442	-877	-1311	-1745	-2180	-2614
	12	1545	1024	503	-18	-540	-1061	-1582	-2103	-2625	-3146	-3667
EIA $25 without Feedback	**6**	1434	1194	953	712	471	229	-24	-284	-545	-805	-1066
	8	1434	1113	792	471	148	-197	-545	-892	-1240	-1587	-1935
	10	1434	1033	632	229	-197	-632	-1066	-1500	-1935	-2369	-2803
	12	1434	953	471	-24	-545	-1066	-1587	-2108	-2630	-3151	-3672
EIA $25 with Feedback	**6**	1713	1472	1231	990	750	509	268	27	-212	-473	-734
	8	1713	1392	1071	750	429	107	-212	-560	-907	-1255	-1602
	10	1713	1311	910	509	107	-299	-734	-1168	-1602	-2037	-2471
	12	1713	1231	750	268	-212	-734	-1255	-1776	-2297	-2818	-3340