Synergies and trade-offs in renewable energy landscapes: Balancing energy production with economics and ecosystem services

Rebecca J. Hanes*, Varsha Gopalakrishnan, and Bhavik R. Bakshi[†]

*William G. Lowrie Department of Chemical and Biomolecular Engineering,
The Ohio State University, Columbus, OH, 43210 USA*

Abstract

Sustainable design methods focus on reducing or minimizing the demand for ecosystem goods and services, quantified as natural resources and pollutant mitigation. However, the capacity of ecosystems to supply these demands is routinely ignored, leading to decisions that overburden ecological processes and cause environmental damage. This work develops a techno-ecological synergy (TES) design methodology that balances the ecosystem services that can be provided by nature with the ecosystem service demands created by human activities. The methodology includes the design of technological processes that require ecosystem services as well as the ecological processes that supply those services. The TES design methodology is demonstrated by application to a renewable energy production system that includes both land use activities, such as agriculture and wind turbines, and biomass conversion activities such as corn ethanol and soybean biodiesel. Under TES Design, the system is optimized to balance the demand and supply of ecosystem services, within constraints imposed on energy production and system economics. The system is also optimized under a more conventional approach that reduces ecosystem service demand while neglecting ecosystem service supply and the relevant ecological processes. Results show that only the TES methodology produces system designs in which ecosystem service supply meets or exceeds the demand. TES system designs produce the same amount of energy as conventional designs, have similar system economics, and use land both for energy production and for ecosystem service supply. The additional supply enables the use of intensive agricultural practices with higher ecosystem service demands and higher biomass yields. These results encourage further efforts toward TES Design with additional ecosystem services.

*Currently at the National Renewable Energy Laboratory, Golden, CO, USA

[†]Corresponding author; email: bakshi.2@osu.edu; tel: +1 614-292-4904

Keywords

Ecosystem services
Sustainability
Renewable energy
Land use trade-offs

1 Introduction

Human activities are sustained by ecosystem services, the resources and benefits provided by natural systems. [1] Ecosystem services include tangible goods, including clean water and crops, as well as less tangible but equally vital benefits such as carbon sequestration, air quality regulation and biodiversity. All human activities create ecosystem service demands, whether through emitting pollutants such as greenhouse gases or through the use of natural and agricultural resources. At present, the demands for ecosystem services created by human activity far outstrips the available ecosystem service supply, which is the capacity of ecosystems to sequester pollutants and provide the required natural goods. [2,3] This situation, called ecological overshoot, has resulted in adverse consequences for humans and for ecosystems, including climate change, soil erosion and quality degradation, and decreases in water quality. [4]

A variety of design methods in different fields of study have been developed to address the interdependencies between ecosystem services and human activity, with the goal of reducing the existing ecological overshoot. Some methods address the role of ecosystem services in agriculture, and explore agricultural management practices and alternate crops that support ecosystem service supply while still providing necessary food, fiber and feedstocks. [5,6] In the field of engineering, sustainable design methods have been developed that optimize technological systems to minimize ecosystem service demand, generally quantified as greenhouse gases or other emissions, at the life cycle scale. [7,8]

These previously developed methods can be used to make decisions that increase relative sustainability by reducing environmental impacts and ecosystem dis-services. However, it is unlikely that these methods will lead to absolute sustainability, in which ecosystem service supply meets or exceeds the demand for all relevant ecosystem services. Achieving absolute sustainability, which can also be defined as a state of zero ecological overshoot, will require methods that simultaneously reduce ecosystem service demand and increase the available supply, by developing synergies between technological and ecological systems. Multiple ecosystem services must be considered, in a rigorous and quantitative manner, and a multi-scale or life cycle boundary must be used, both to avoid shifting ecosystem service demands outside of the analysis boundary and to capture ecosystem services at the appropriate scale.

In this paper the concept of techno-ecological synergy (TES) is used to develop a design methodology that incorporates simultaneous technological and ecological decision making, a life cycle system boundary, and both demand and supply for multiple ecosystem services. [9] The proposed TES design methodology is demonstrated by application to a renewable energy production system located in central Ohio. Renewable energy systems were chosen as the application in this work because the sustainability - as well as the economic and technical feasibility - of such systems depends upon balanced interactions between technological and ecological processes. [10,11] However, the present methodology is intended as a special case of a general TES design methodology, still under development, that can be applied to design any type of system at any scale, from a single private home to a regional biofuel supply chain or national renewable electricity grid.

Results of applying the TES design methodology to a renewable energy system will demonstrate three benefits of TES design. First, TES design leads to unique designs with higher sustainability compared to conventional life cycle design. Second, the use of TES in designing renewable energy systems enables identification of synergies between the technological and ecological system components that are not apparent under life cycle designs and other technology-centric designs. Finally, the use of TES in design allows for the evaluation of trade-offs between multiple objectives: monetary value, renewable energy production, and the ecosystem services air quality regulation and climate regulation. Under TES design, intensive agricultural farming practices are used to produce biomass efficiently, and the ecosystem service demands created by these practices are offset by additional land used to create ecosystem service supply. While the purpose of this work is not to make policy recommendations or to promote one kind of renewable energy over others, knowledge of the trade-offs between the many goods and services provided by land use can be applied to determine how much value can be economically and sustainably extracted from the land.

The literature review in Section 2 provides an overview of studies that incorporate aspects of TES, in order to convey the novelty and uniqueness of the proposed approach. Section 3 presents the methodology for applying TES design to a renewable energy system. Key results that demonstrate the benefits of TES design are discussed in Section 4, with additional results presented in the Annexes. Section 5 presents conclusions of this work and discusses future work.

2 Literature Review

The five core concepts of TES design described in Section 1 are, by themselves, not novel; the novelty of this work is that these five concepts have not previously been integrated into a cohesive methodology for application to a single design problem. This section gives an overview of recent studies that use at least two of the five TES concepts in a design context. Table 1 lists these studies along with the corresponding TES concepts.

Zhang et al. [12] developed a modeling framework to optimize biofuel feedstock production while accounting for trade-offs between agricultural productivity and demand for several ecosystem services; however, the supply of only one ecosystem service, carbon sequestration, was quantified. Eranki et al. [13] develop a similar model to design a cellulosic biofuel feedstock supply chain by allocating land to feedstock production, with the additional constraint that animal nutrition needs also be met. This study incorporated a life cycle assessment of the supply chains being designed and also quantified multiple ecosystem services, although the balance between demand and supply for individual services was not considered. Meehan et al. [14] modeled ecosystem service trade-offs of using the same land for either corn or perennial grasses, and considered both potential energy production and feedstock economics. In a similar study, Davis et al. [15] quantified the ecosystem service impacts of land used to produce different biofuel feedstocks. Behrman et al. [16] and Meyer et al. [17] also consider land use for biofuel, but quantify only the impacts on ecosystem service supply. Although the focus of these studies is on supplying feedstock to biofuel or bioenergy production, none of these studies consider technological design variables, and in each study the type of feedstock and energy product produced is fixed. With the exception of [13], these studies also neglect the life cycle of the systems being designed, which can lead to environmental impacts and ecosystem disservices being shifted outside the analysis boundary rather than being avoided altogether.

Studies that focus primarily on technological design include You et al. [18], Čuček et al. [19] and Hanes and Bakshi [20], among many other similar works. You et al. combine a supply chain model with a life cycle assessment of the supply chain in order to optimize the supply chain and its life cycle for minimum emissions. Čuček et al. take a similar approach to select biomass conversion

Table 1: Previous studies that incorporate one or more aspects of TES design.

Source	Technological Design	Ecological Design	Life Cycle Scale	Ecosystem Service Demand	Ecosystem Service Supply
This work	X	X	X	X	X
[12]		X		X	X
[13]		X	X	X	X
[14]		X		X	X
[15]		X		X	X
[16]		X			X
[17]		X			X
[18]	X		X	X	
[19]	X		X	X	
[20]	X		X	X	
[21]	X	X	X	X	
[22]	X	X	X	X	
[23]	X	X		X	
[24]		X		X	X
[25]	X	X		X	X
[26]	X	X		X	X

technologies according to environmental impacts at the life cycle scale. Hanes and Bakshi use a multi-scale model to minimize emissions from an ethanol plant and its life cycle within a national system boundary. While each of these studies includes the technological design variables and life cycle that the previous set of studies largely lacked, ecosystem service supply and ecological design are uniformly excluded. These studies thus risk making decisions that minimize environmental impacts and ecosystem service demand but still do not approach absolute sustainability, due to the ecosystem service demand still far outweighing the available supply.

Some more general studies have also focused on developing frameworks that can predict the complex interplay between changes in ecosystem services and energy production systems. Howard et al. [21] developed a framework for incorporating the entire energy landscape including supply, demand and infrastructure available for energy production at a local scale, and measured how these systems interact with ecosystem services. However, main focus of this work was to build a framework for decision making by accounting for stakeholder preferences and not for identifying optimal design pathways. Guo et al. [22] developed a modeling framework that considers the competition between land used by different economic sectors, and the impacts of land-use change on multiple ecosystem services across the entire value chain. Gonzalez et al. [23] developed a modeling framework accounting for the interactions between energy, economy, land use and greenhouse gas emissions for emerging bioenergy production systems in developing countries. However, the latter two frameworks do not account for the entire life cycle of the system and ignore the ecosystem service supply entirely.

Finally, there have been several studies that focus on quantifying the interactions between technological systems and ecosystems via quantification of ecosystem service demand and supply. Gopalakrishnan et al. [24] assessed the importance of ecosystem services in supporting an industrial

site by quantifying the demand and supply of multiple ecosystem services at a local scale. However, this study does not account for life cycle emissions and ignores aspects of technological design. Urban et al. [25] designed a techno-ecological North American residential system by accounting for both demand and supply of ecosystem services, and included behavioral, ecological and technological decision variables. Martinez-Hernandez et al. [26] used a system dynamics approach to analyze the impacts of bioenergy production on services provided by a dynamic heathland ecosystem. The latter two studies incorporate all aspects of TES design except for the life cycle boundary. Solutions found in these studies therefore risk shifting the ecosystem service demand to activities outside the analysis boundary.

The studies and methods discussed above are each missing some key aspect of TES design and therefore solve only part of the problem, and in so doing are likely to lead to sub-optimal or simply incorrect solutions [27]. The primary contribution of this work, the TES design methodology, is an attempt to solve the entire problem, by framing the design problem in terms of achieving balance between demands placed on ecosystems and the ability of ecosystems to satisfy those demands, while still maintaining a profitable and productive system.

3 Materials and Methods

In this section, methods for applying TES in a design context and for building a renewable energy system model for optimization are discussed. Details on the specific model built in this work are given, along with the source data and assumptions used in building the model. Finally, the optimization formulation used to solve the model and generate renewable energy system designs is discussed.

3.1 Techno-ecological synergy design concept

The TES design methodology is used to make simultaneous technological and ecological design decisions within a multi-scale system in order to both decrease demand and increase supply of multiple ecosystem services. [9] This is intended to avoid the risk of identifying sub-optimal design decisions that either shift ecosystem service demand and the accompanying environmental impacts outside the system boundary, or decrease ecosystem service demand without considering if the decreased demand can be sustainably supplied by supporting ecosystems. TES design also promotes land use and other activities that preserve and restore ecological functions and increase the available ecosystem service supply. TES design is in contrast with the more conventional life cycle design, in which a technological system is designed within its life cycle to minimize ecosystem service demand and the role of ecological systems in supporting the technological system is neglected. Specific TES design requirements, contrasted with the requirements for conventional life cycle based design, are given in Table 2.

The TES design methodology requires modeling systems at multiple scales. The scale of ecological systems varies from local, regional to global depending on the serviceshed of the ecosystem service of interest, which is the maximum scale at which the ecosystem service can be supplied. [9,28] Typically, ecosystem services like water quality regulation are modeled at the local or regional (watershed) scale, while services like carbon sequestration, with global servicesheds, can be modeled at the local, regional and global scales. Some ecosystem services, such as pollination, have servicesheds limited by the area traveled by pollinators and are modeled at smaller scales. The supply of smaller-scale ecosystem services is also spatially specific and depends on multiple factors such as local meteorological conditions, land use practices and the availability of ecological systems at a given scale. Technological systems can vary from individual processes at the local scale to aggregate

Table 2: Requirements for TES design contrasted with conventional life cycle design.

TES Design	Life Cycle Design
<ul style="list-style-type: none"> • Simultaneous design of technological and ecological systems • Inclusion of ecosystem service demand and ecosystem service supply in design criteria • Inclusion of multiple ecosystem services and goods (bundles) in design criteria • Consideration of technological and ecological systems at multiple scales, up to the life cycle or larger scale 	<ul style="list-style-type: none"> • Design of technological systems • Inclusion of ecosystem service demand in design criteria • Occasional inclusion of multiple ecosystem services in design criteria • Consideration of technological systems up to the life cycle scale

activities at the larger, life cycle scale. Within a particular spatial scale, both the technological systems that create ecosystem service demand and the corresponding ecological systems that create the ecosystem service supply should be included. The expanded system boundary enables the identification and exploitation of synergies and trade-offs between technological and ecological systems, as well as synergies and trade-offs between the various ecosystem services and between systems at different scales.

TES design requires quantifying ecosystem service demand and supply at each relevant spatial scale, in order to determine the extent to which the demand for an ecosystem service overshoots the supply and to make decisions that decrease or eliminate the overshoot. The sustainability index V_{jk} is a TES metric defined for each ecosystem service k at each relevant spatial scale j that quantifies this overshoot: [9]

$$V_{jk} = \frac{S_{jk} - D_{jk}}{D_{jk}} \quad (1)$$

In Equation 1, D_{jk} is the demand for ecosystem service k , and S_{jk} is the supply. As discussed in Section 1, ecosystem service demand is quantified by resource use or emissions, while supply is quantified by the capacity of an ecological system to supply the resources demanded or to mitigate the pollution produced.

The sustainability index V_{jk} has multiple uses in the TES design methodology: as an indicator of the degree of unsustainability or sustainability, as an objective function, and as a metric to compare different systems and system designs. V_{jk} is designed such that when Equation (2) holds true:

$$V_{jk} \geq 0 \quad (2)$$

the supply of ecosystem service k equals or exceeds the demand at scale j , which indicates sustainable use of service k . More strongly, when Equation (2) holds true at a scale j equal to the serviceshed of service k , this indicates absolute sustainability for service k . In contrast, a negative V_{jk} indicates unsustainable use of service k . The minimum value of V_{jk} is -1, which indicates that no significant supply of service k is available at scale j . When $V_{jk} < 0$, ecosystems cannot supply sufficient services to meet the demand created by technological systems without causing harmful ecological degradation and a further decrease in the ecosystem's ability to supply the necessary services. For instance, $V_{jk} < 0$ for carbon sequestration at the local scale indicates that local ecosystems do not have the capacity to mitigate the greenhouse gas emissions being produced,

and the technological system must depend on carbon sequestration supplied from larger scales or different geographic locations.

3.2 Options for renewable energy production

Two general categories of activities must be included in the design of a renewable energy production system. First is land use activities, which may be agricultural activities that produce biomass feedstocks to be converted to energy carriers, or technological activities that produce electricity or heat directly. Land use activities may also supply ecosystem services in addition to or instead of supplying biomass or energy. The second activity category is biomass conversion activities, which convert biomass feedstocks into electricity, heat or biofuels. Exactly which activities to consider in each category should be informed by the geographic location of the system being designed, along with the meteorological and agricultural characteristics of that location. The economic and technical feasibility of each activity should also be considered, particularly how the activity’s feasibility is affected by the geographic location. For instance, concentrated solar power (CSP) is a land use activity that generates electricity is becoming more feasible as the technology advances, but even if CSP becomes cheap and reliable in the desert regions of the American Southwest, it will not be economic in the cloudier, rainier Pacific Northwest region. Similarly, corn farming for starch or cellulosic ethanol is concentrated in the “Corn Belt,” located in the American Midwest, because the climate and soil in that region grows corn very efficiently.

Because this work focuses on renewable energy in central Ohio, the land use and biomass conversion activities chosen reflect both activities that are already established in the region and those activities which have the potential to be economically and technically feasible, but are not yet established. The complete set of land use and biomass conversion activities considered, and the potential connections between activities, are shown in Figure 1. Land use activity options, in red in Figure 1, are continuous corn, corn-soybean rotation, and perennial switchgrass cropping systems, wind turbines and solar panels. Each cropping system activity is modeled under two types of farming practice, a standard, intensive farming practice (conventional tillage, switchgrass with nitrogen fertilizer) and conservation practice (no tillage, switchgrass without nitrogen fertilizer). The conservation farming practices are intended to promote ecosystem service supply at the farm scale. Additional land use activity options which solely supply ecosystem services are shown in green in Figure 1. These are all reforestation activities, with six native Ohio tree species. Each of the tree species supplies ecosystem services, although the growth rate and tree characteristics, which vary by species, determine which services are supplied and at what rate.

The biomass conversion activities, shown in blue in Figure 1, include both commercial processes and processes still in development or at the pilot stage. To correspond with the land use activities being considered, corn ethanol, cellulosic ethanol and soybean biodiesel are included, as are the less well-developed biomass pyrolysis and hydrotreating and biomass combustion. Each biomass conversion activity can utilize the feedstock from multiple land use activities, increasing the total number of possible energy production pathways in the design space.

3.3 Design scenarios

The energy production system is optimized under two design scenarios in order to compare and contrast the results of conventional life cycle design with the TES design methodology. These scenarios are based on the criteria laid out in Table 2. In the first scenario, Life Cycle Design, the model is optimized, separately, for economics, energy production, and the system’s demand for key ecosystem services. Land can be used only for fuel and energy production; reforestation to create additional ecosystem service supply is not permitted. The supply of ecosystem services

Figure 1: The renewable energy production system superstructure, which contains land use and biomass conversion activities for every energy production pathway considered.

provided by agricultural land use activities is also not considered. In the second scenario, TES Design, the economics and energy production objective functions are identical to those under Life Cycle Design. However, instead of minimizing ecosystem service demand, net ecosystem service supply, quantified by supply minus demand, is maximized. Recall that ecosystem service supply is quantified as the ability of ecosystems to sequester or mitigate pollutants, while ecosystem service demand is quantified as pollutant production or natural resource consumption. Net ecosystem service supply is equal to the numerator of Equation (1) ($S_{jk} - D_{jk}$); the numerator is optimized rather than Equation (1) to keep the model linear. TES Design also allows for land to be used for reforestation rather than energy production to increase the supply of ecosystem services. As the total amount of land available is the same in both design scenarios, land used for ecosystem service supply competes with land used for energy production.

3.4 Model structure and constraints

To determine the optimal combinations of land use activities and biomass conversion pathways, a mixed-integer linear program (MILP) representation of the superstructure shown in Figure 1 is developed. The MILP was solved a total of sixteen times. Solutions were found for four objective functions under the two design scenarios described in 3.3 and under each of two energy production constraints. Further details on the MILP, objective functions and design scenarios are given in this section. The model was implemented in Python and solved using `lp_solve`. [29]

The various combinations of activities in the energy production system, and the life cycles of those activities, are captured using the multi-scale process to planet (P2P) modeling framework. [30] The P2P framework connects component models at three different scales: local, regional and national. At the local scale, component models are detailed and specific to a technological process or facility. For instance, a local scale model might represent a particular biodiesel plant. Regional scale component models are less detailed and represent a regional, state or county-average activity, such as farming practices in a particular geographic area. The national scale component model, the least detailed, represents a national economy. Component models are connected by monetary and material exchanges and used to form a set of multi-scale mass, energy and monetary balances on the system and its life cycle:

$$\begin{bmatrix} \bar{\mathbf{I}} - \bar{\mathbf{A}}^* & -\underline{\mathbf{X}}_u & -\mathbf{X}_u^E \\ \underline{\mathbf{0}} & \underline{\mathbf{X}} & -\mathbf{X}_u^V \\ \mathbf{0} & \mathbf{0} & \mathbf{X} \end{bmatrix} \begin{bmatrix} \bar{\mathbf{s}} \\ \underline{\mathbf{s}} \\ \mathbf{s} \end{bmatrix} = \begin{bmatrix} \underline{\mathbf{0}} \\ \underline{\mathbf{0}} \\ \mathbf{0} \end{bmatrix} \quad (3)$$

The vectors $\bar{\mathbf{s}}$, $\underline{\mathbf{s}}$ and $\mathbf{s}$ are decision variables at the national, regional and local scales respectively, and are defined in Section 3.11. Matrices in the first line of Equation (3) represent monetary flows that originate in economic sectors, at the national scale. $\bar{\mathbf{A}}^*$ is the disaggregated direct requirements matrix, derived from the 2002 benchmark input-output model of the U.S. economy developed by the Bureau of Economic Analysis. [31] $\bar{\mathbf{I}}$ is the identity matrix of the same dimensions as $\bar{\mathbf{A}}^*$. The original direct requirements matrix $\bar{\mathbf{A}}$ was disaggregated to $\bar{\mathbf{A}}^*$ to avoid double-counting land use and biomass conversion activities that are modeled at the regional and local scales respectively. [30]

$\underline{\mathbf{X}}_u$ in Equation (3) contains, in monetary units, the amounts of fertilizer, fuel and other inputs required by each land use activity per acre. $\underline{\mathbf{X}}$ also contains the purchase, installation and maintenance costs per unit for wind turbines and solar panels. The production and distribution of these flows, representing the life cycle of the land use activities, is captured at the national scale. Similarly, $\mathbf{X}_u^E$ contains, also in monetary units, the amounts of fuels, chemicals, process equipment and other inputs required by the biomass conversion plants, and represents the life cycle of the

biomass conversion plants. Taken together, the first line of Equation (3) represents a monetary balance on the national scale model, and is interpreted as stating that no flows leave the economy save for those required by the energy production activity models.

Matrices in the second line of Equation (3) represent physical unit flows originating in the land use activities, including the cropping systems, the wind turbines and the solar panels. $\underline{\mathbf{X}}$, in physical units, contains the biomass production per acre for the cropping systems and the electricity production per unit for wind turbines and solar panels. (Recall that inputs to the cropping systems, wind turbines and solar panels are modeled as flows originating in the economy and are represented in the matrix $\underline{\mathbf{X}}_u$.) $\underline{\mathbf{X}}_u^V$, in physical units, contains the flows of biomass per plant for each biomass conversion process. The second line of Equation (3) thus represents a mass balance on corn, soybean and cellulosic biomass flows, and also represents the amount of electricity produced by wind turbines and solar panels. This line of the equation is constrained to be greater than or equal to zero, meaning that all type of biomass and particularly food products can be sold as is, instead of being converted to energy.

The third line of Equation (3) contains a physical-units matrix $\underline{\mathbf{X}}$ that represents the end product yields for the biomass conversion processes. (Recall that non-biomass inputs to the plants are captured in $\underline{\mathbf{X}}_u^E$ as monetary flows originating in the economy, and that the biomass inputs are captured in $\underline{\mathbf{X}}_u^V$ as physical flows originating in the land use activities.) The third line of Equation (3) is also constrained to be greater than or equal to zero, allowing for energetic end products to leave the system. To simplify the analysis, all energetic products are assumed to be used for transportation. This assumption allows the energetic end products to be quantified in gasoline gallon equivalents (GGEs) and enables direct comparison between all possible system designs.

There are three zero matrices in Equation (3), forming the lower triangular matrix. These matrices represent flows back to the national scale that originate at the local and regional scales. Because these matrices consist of zeros, there are no such flows in the system model.

3.5 Land use and reforestation constraints.

The total acreage of all land use activities, including cropping systems, wind turbines and solar panels, and reforestation, is constrained to be less than or equal to 10,000 acres:

$$\underline{\mathbf{A}} \cdot \begin{bmatrix} \underline{\mathbf{s}} \\ \underline{\mathbf{t}} \end{bmatrix} \leq 10,000 \text{ acres} \quad (4)$$

The elements of $\underline{\mathbf{A}}$ are given in Table 9.

The Life Cycle Design scenario does not allow for reforestation and an additional constraint on $\underline{\mathbf{t}}$:

$$\underline{\mathbf{t}} = \mathbf{0} \quad (5)$$

is necessary to constrain all elements of $\underline{\mathbf{t}}$ to zero. The TES Design scenario allows reforestation, thus Equation (4) is sufficient to constrain the land use activity acreage. Note that under TES Design, there is no explicit upper limit placed on the acres of reforestation. Instead, reforestation is implicitly constrained by the energy production and net present value constraints discussed below.

3.6 Energy production and NPV constraints.

Several constraints are imposed to restrict the design space under both scenarios to economically and technologically feasible systems. The NPV of the entire system, including agricultural activities,

wind turbines and solar panels, reforested land and all biomass conversion processes, is constrained to be greater than or equal to zero:

$$\mathbf{N} \cdot \begin{bmatrix} \underline{\mathbf{s}} \\ \underline{\mathbf{t}} \\ \underline{\mathbf{s}} \end{bmatrix} \geq 0 \quad (6)$$

The elements of $\mathbf{N}$ are given in Table 9. A lower limit is also imposed on the amount of energy produced by the system. Unlike the NPV constraint, two values of the energy production constraint are defined relative to the maximum possible energy production. Sets of solutions were found for energy production greater than or equal to 10% of the maximum:

$$\mathbf{E} \cdot \begin{bmatrix} \underline{\mathbf{s}} \\ \underline{\mathbf{t}} \\ \underline{\mathbf{s}} \end{bmatrix} \geq 0.1E_{\max} \quad (7)$$

and for greater than or equal to 90% of the maximum:

$$\mathbf{E} \cdot \begin{bmatrix} \underline{\mathbf{s}} \\ \underline{\mathbf{t}} \\ \underline{\mathbf{s}} \end{bmatrix} \geq 0.9E_{\max} \quad (8)$$

The two sets of solutions are referred to in subsequent sections as “Low Energy Production” and “High Energy Production” designs, respectively. Finding solutions for multiple values of this constraint rather than fixing the value allows for an analysis of trade-offs between energy productivity, ecosystem services and economics. The elements of $\mathbf{E}$ are given in Table 9. In Equations (7) and (8), $E_{\max}$ is defined as

$$E_{\max} = 9.59 \times 10^7 \text{ GGE} \quad (9)$$

The maximum energy production value was found by solving the MILP for maximum energy while constraining the NPV to be greater than or equal to zero. This is the maximum possible energy production from the system being considered, and does not change under different design scenarios.

3.7 Biomass conversion, wind turbine and solar panel models

Table 3 lists the sources of data used to build the biomass conversion process, wind turbine and solar panel models. Each biomass conversion process model contains a set of process inputs and energy outputs scaled to the consumption of one unit of biomass feedstock. Emissions factors from GREET 2015 were used to model process fuel combustion. [32] Prices for commodity chemical inputs were obtained from ICIS [33], and fuel and energy prices were obtained from the Energy Information Administration. [34–38] Prices for inputs that could not be found within these sources were obtained from online retailers. Where possible, input prices and other economic data were obtained for the year 2002; any prices not already at 2002 levels were converted using producer price index data from the U.S. Bureau of Labor Statistics. [39] Each plant’s twenty-year NPV is calculated from the total installed equipment cost (obtained from sources cited in Table 3), the revenue from sales of energy products, and other economic parameters. [40]

To build the energy production system model, each of the biomass conversion process models was scaled to represent the maximum possible capacity of each plant. The maximum capacity was based on the maximum availability of each type of biomass feedstock. For instance, the corn ethanol process model was scaled to the amount of corn produced by the continuous corn, no till cropping system, which produced the most corn out of the four corn-producing cropping systems. Scaling the baseline process models in this way allows the models to be scaled linearly by the amount of

Table 3: Summary of data sources for wind turbine, solar panel and biomass conversion process models.

Model	Source(s) of model data
Wind Turbine	[41–44]
Solar Panel	[41, 45]
Corn Ethanol	[46, 47]
Soybean Biodiesel	[32, 48–51]
Stover Ethanol	[46, 47, 52]
Switchgrass Ethanol	
Stover Pyrolysis	[53–55]
Switchgrass Pyrolysis	
Stover Combustion	[32, 56]
Switchgrass Combustion	

available feedstock, which depends on the type and acreage of the active cropping systems, during optimization. The linear process scaling is not ideal, as economies of scale cannot be captured; this is particularly significant in calculating the economic objective function, which is the sum of the net present values of each system component. For this reason NPV is referred to as “Linearized NPV” in Section 4. Using linear scaling leads to very small-scale process models appearing to be more efficient and economical than they would be in reality. However, keeping the scaling linear also keeps the system model linear, which ensures that a global optimum will be found for each objective function.

The source data, including biomass conversion processes and all relevant input prices, were largely from 2002. The purpose of this work is to demonstrate that engineering design decisions made based on ecosystem services will change depending on whether only ecosystem service demand is considered or both supply and demand. The age of the data is thus expected to have little to no impact on the major conclusions of this work.

3.8 Farming activity models

Farming activities were modeled using the Environmental Policy Integrated Climate (EPIC) software for Windows (WinEPIC) [57, 58] to create a spatially specific model for each cropping system. As model inputs, WinEPIC requires spatially and temporally specific information on climate, [59, 60] farming management practices [61–63] and soil type [64]. To extend the meteorological data to cover the full twenty year time period, data for the first three years (1995 - 1998) was used as proxy data for the final years (2011 - 2014). All farming activities including fertilizer requirements, pesticide application rate and other farming decisions were identical each year, depending on the crop type. Default planting and harvesting calendars in WinEPIC were used to specify the dates of all plantings, fertilizer applications, harvests, and other activities. Given this input data, WinEPIC calculates carbon and nitrogen flows (including both sequestration and releases) and crop yields on both daily and annual bases.

Table 4 gives the climate regulation and air quality regulation demand and supply created by the cropping systems over twenty years, calculated using WinEpic as discussed above. The fertilized switchgrass cropping system has the highest climate regulation demand per acre, due to decaying crop residues that release CO₂ emissions in addition to the CO₂ and N₂O emissions generated from the use of farming equipment. However, the climate regulation supply is also highest for this cropping system, as the crop residues also return carbon to the soil. Air quality regulation demand

Table 4: Ecosystem service demand and supply for farming activities over twenty years.

Cropping System	Climate Regulation (kg CO ₂ -eq/acre)		Air Quality Regulation (kg NO ₂ /acre)	
	Demand	Supply	Demand	Supply
Cont. Corn, No Till	6.83×10^4	2.54×10^3	2.28×10^1	0
Cont. Corn, Conv. Till	7.30×10^4	2.48×10^3	3.72×10^1	0
Corn-Soybean, No Till	6.37×10^4	2.66×10^3	2.26×10^1	0
Corn-Soybean, Conv. Till	5.96×10^4	2.52×10^3	3.36×10^1	0
Switchgrass, No N Fert.	5.67×10^4	3.24×10^3	1.10×10^1	0
Switchgrass, With N Fert.	6.07×10^4	3.23×10^3	1.28×10^1	0

is highest for the continuous corn, conventional tillage cropping system, due to the increase in NO₂ emissions from the use of farm equipment.

3.9 Forest ecosystem model

Carbon sequestration by reforested land was modeled at the regional scale, using the iTree Design software suite and functions to predict tree height and crown diameter. [65,66] Six tree species native to Ohio that were considered in this study include white oak, Scots pine, American elm, spruce, birch and eastern hemlock. [67] Tree height and crown diameter were estimated for each tree species using height-age and diameter-height functions for twenty year old open grown trees. [66] Climate regulation and air quality regulation supplies per tree, under average conditions for west-central Ohio, were then estimated per tree using the iTree design tool. [68] Reforestation was assumed to create no ecosystem service demand regardless of tree species. The ecosystem service supplies are given in Table 5.

Table 5: Ecosystem service demand and supply from reforestation over twenty years.

Tree Species	Climate Regulation (kg CO ₂ -eq/tree)		Air Quality Regulation (kg NO ₂ /tree)	
	Demand	Supply	Demand	Supply
White oak	0	1.61×10^4	0	2.96
Scots pine	0	8.65×10^4	0	2.94
American elm	0	1.23×10^4	0	2.96
Spruce	0	1.31×10^4	0	2.97
Birch	0	1.19×10^4	0	2.93
Eastern hemlock	0	5.24×10^4	0	3.00

3.10 Scale of ecosystem services

The scale at which the ecosystem service demand and supply is modeled depends on the largest scale which is relevant for that service and for which data is available. For the system considered

here, the climate regulation demand is quantified with emissions of two greenhouse gases, nitrous oxide (N₂O) and carbon dioxide (CO₂). N₂O emissions are modeled at the local and regional scales. N₂O emissions were not included at the economy scale due to a lack of data, and because at that scale N₂O emissions are expected to be insignificant compared to CO₂ emissions. CO₂ emissions are modeled at all three scales, local, regional and national. The third greenhouse gas commonly accounted for, methane, was not considered in this study. Methane is produced in very low quantities by the agricultural and biomass conversion activities, and it is not taken up in significant quantities by either reforestation or agriculture. The additional climate regulation demand and supply due to the emission and sequestration of methane is thus taken as negligible compared to the demand and supply due to N₂O and CO₂ emission and sequestration. [69]

The supply of climate regulation, quantified by carbon sequestration, is provided only by agricultural activities and by reforestation, thus it is modeled at the regional scale. Although carbon sequestration data is available at the national scale [70], it was not included in this model due to issues related to the allocation of ecosystem service supply and the presence of carbon trading schemes that are beyond the scope of this work.

Air quality regulation is modeled only at the regional and local scales, as its serviceshed, which depends on the maximum distance of pollutant dispersion, is a relatively small spatial area. Air quality regulation demand, quantified with NO₂ emissions, is created both by the farming activities and by the biomass conversion processes, while supply is provided at the regional scale by reforestation.

In accounting for CO₂ emissions and carbon sequestration, all biogenic emissions and short-term carbon sequestration are excluded. Biogenic emissions come from carbon in the biomass being converted to fuel, and the short-term carbon sequestration is provided by carbon uptake in growing crops. These emissions and sequestration are two components in the short-term carbon sequestration/emission cycle that consists of biomass growth, conversion to fuel, and fuel use. The amount of carbon involved in the cycle varies, but the amount of carbon released in biomass conversion and fuel usage is approximately equal to the carbon taken up by the next cycle of biomass growth for all energy products. Because the fuel usage phase is not included in the design boundary, the carbon balance cannot be closed for all energy products. Excluding all biogenic emissions and short-term carbon sequestration is therefore necessary to avoid giving some energy products, which do not release a significant amount of biogenic CO₂ until the use phase, an unfair advantage over other products that release a greater proportion of biogenic CO₂ during biomass conversion. For the same reason, carbon taken up in the biomass that gets converted to fuel or sold as food is not included in the climate regulation supply. The only CO₂ emissions included in the climate regulation demand are from fossil sources, and the only carbon sequestration included in the supply is long-term sequestration in agricultural soil and in forest biomass, which is not harvested. Table 6 summarizes the scales at which the demand and supply of different ecosystem services are quantified.

3.11 Decision variables and ranges

Decision variables within the optimization problem are expressed as vectors. $\bar{\mathbf{s}}$ represents the amount of economic activity in each economic sector, in units of millions of USD. The vector $\underline{\mathbf{s}}$ represents the acreage of each cropping system and the numbers of wind turbines and of solar panels installed:

$$\underline{\mathbf{s}} = \left[\underline{s}_{CCNT} \quad \underline{s}_{CCCT} \quad \underline{s}_{CSNT} \quad \underline{s}_{CSCT} \quad \underline{s}_{SNF} \quad \underline{s}_{SWF} \quad \underline{s}_{WT}^I \quad \underline{s}_{SP}^I \right]^T. \quad (10)$$

Table 6: Scale of component models and ecosystem services.

Scale	Component Models	Climate Regulation	Air Quality Regulation
Local	Biomass Conversion Processes	Demand	Demand
Regional	Farming Activities	Demand and Supply	Demand
	Wind Turbines	<i>assumed negligible</i>	<i>assumed negligible</i>
	Solar Panels	<i>assumed negligible</i>	<i>assumed negligible</i>
	Reforestation	Supply	Supply
National	Life Cycle Activities	Demand	

Elements of $\underline{\mathbf{s}}$ correspond to the land use activities shown in red (both ovals and rectangles) in Figure 1. The superscript I indicates that the wind turbine and solar panel scaling factors are integer variables; the rest of the land use scaling factors are continuous variables. $\underline{\mathbf{t}}$ represents the number of trees of each tree species planted as reforestation:

$$\underline{\mathbf{t}} = \begin{bmatrix} t_{WO} & t_{ScP} & t_{AE} & t_{Sp} & t_{Bi} & t_{EH} \end{bmatrix}^T. \quad (11)$$

All of the reforestation variables, which correspond to the green ovals in Figure 1, are integer variables. Finally, $\mathbf{s}$ represents the (unitless) scale of each biomass conversion process:

$$\mathbf{s} = \begin{bmatrix} s_{CornEth} & s_{SoyBiod} & s_{SwiEth} & s_{StoEth} & s_{SwiPyr} & s_{StoPyr} & s_{SwiCom} & s_{StoCom} \end{bmatrix}^T. \quad (12)$$

Biomass conversion plant scaling factors are constrained to be less than one:

$$\mathbf{s} \leq 1. \quad (13)$$

Elements of $\mathbf{s}$ correspond to the blue rectangles shown in Figure 1. The elements of $\bar{\mathbf{s}}$, $\underline{\mathbf{s}}$, $\underline{\mathbf{t}}$ and $\mathbf{s}$ are all non-negative. Table 7 gives expanded definitions of the elements of $\underline{\mathbf{s}}$, $\underline{\mathbf{t}}$ and $\mathbf{s}$.

The number of wind turbines and the number of solar panels, $\underline{s}_{WT}^I$ and $\underline{s}_{SP}^I$, are constrained as follows. The number of wind turbines may not exceed 500:

$$\underline{s}_{WT}^I \leq 500. \quad (14)$$

This upper limit was calculated from sources given in Table 3, based on keeping a safe distance between wind turbines. An upper limit is likewise imposed on the number of solar panels:

$$\underline{s}_{SP}^I \leq 57,812,156. \quad (15)$$

The limit was calculated based on the land area occupied by each solar panel unit.

3.12 Objective functions

The set of objective functions under Life Cycle Design and under TES Design are listed in Table 8 and are defined in Equations (16) - (21). All of the objective functions in all scenarios represent the twenty-year operating period, such that the energy production objective function represents twenty years of fuel and electricity production, climate regulation demand represents CO₂ and N₂O emissions from twenty years of system operation, and so on for the rest of the objective functions.

Table 7: Definitions of variables in optimization equations. Variables are continuous unless otherwise noted.

Term	Definition
$\bar{s}$	Millions of dollars of economic activity from each economic sector
$\underline{s}_{CCNT}$	Acres of continuous corn, no tillage
$\underline{s}_{CCCT}$	Acres of continuous corn, conventional tillage
$\underline{s}_{CSNT}$	Acres of corn-soybean, no tillage
$\underline{s}_{CSCT}$	Acres of corn-soybean, conventional tillage
$\underline{s}_{SNF}$	Acres of switchgrass, no N fertilizer
$\underline{s}_{SWF}$	Acres of switchgrass with N fertilizer
$\underline{s}_{WT}^I$	Number of wind turbines (integer variable)
$\underline{s}_{SP}^I$	Number of solar panels (integer variable)
$s_{CornEth}$	Corn ethanol plant scaling factor
$s_{SoyBiod}$	Soybean biodiesel plant scaling factor
s_{SwiEth}	Switchgrass ethanol plant scaling factor
s_{StoEth}	Stover ethanol plant scaling factor
s_{SwiPyr}	Switchgrass pyrolysis plant scaling factor
s_{StoPyr}	Stover pyrolysis plant scaling factor
s_{SwiCom}	Switchgrass combustion plant scaling factor
s_{StoCom}	Stover combustion plant scaling factor
$\underline{t}_{WO}$	Number of white oak trees (integer variable)
$\underline{t}_{ScP}$	Number of Scots pine trees (integer variable)
$\underline{t}_{AE}$	Number of American elm trees (integer variable)
$\underline{t}_{Sp}$	Number of spruce trees (integer variable)
$\underline{t}_{Bi}$	Number of birch trees (integer variable)
$\underline{t}_{EH}$	Number of Eastern hemlock trees (integer variable)

Table 8: Objective functions under the Life Cycle Design and TES Design scenarios.

Objective Function	Life Cycle Design	TES Design
Maximize NPV, $Z_{\mathbf{N}}$	X	X
Maximize energy production, $Z_{\mathbf{E}}$	X	X
Minimize climate regulation demand, Z_{Δ_C}	X	
Maximize net climate regulation supply, Z_{Σ_C}		X
Minimize air quality regulation demand, Z_{Δ_A}	X	
Maximize net air quality regulation supply, Z_{Σ_A}		X

The objective functions in Table 8 are expressed as linear combinations of decision variables, with coefficient vectors that are specific to each function. The energy production objective function $Z_{\mathbf{E}}$ is expressed as

$$Z_{\mathbf{E}} = \mathbf{E} \cdot \begin{bmatrix} \underline{s} \\ \underline{t} \\ \underline{s} \end{bmatrix} \quad (16)$$

in which $\mathbf{E}$ is a vector of energy production values: the total amount of fuel and electricity, in GGE, produced by each land use activity and biomass conversion process over twenty years. The elements of $\mathbf{E}$ are zero except for the wind turbines, solar panels, and biomass conversion processes, indicating that energetic end products are only directly produced by these activities.

All four of the remaining objective functions are calculated similarly to $Z_{\mathbf{E}}$. The net present value objective function is

$$Z_{\mathbf{N}} = \mathbf{N} \cdot \begin{bmatrix} \underline{s} \\ \underline{t} \\ \underline{s} \end{bmatrix} \quad (17)$$

in which the elements of $\mathbf{N}$ are twenty-year net present values for each individual activity. The system NPV is thus calculated as a linear combination of the individual activities.

The climate regulation demand objective function is

$$Z_{\Delta_C} = \Delta_C \cdot \begin{bmatrix} \overline{s} \\ \underline{s} \\ \underline{t} \\ \underline{s} \end{bmatrix} \quad (18)$$

and the climate regulation net supply objective function is

$$Z_{\Sigma_C} = \Sigma_C \cdot \begin{bmatrix} \overline{s} \\ \underline{s} \\ \underline{t} \\ \underline{s} \end{bmatrix}. \quad (19)$$

Equation (18) only applies in the Life Cycle Design scenario, and Equation (19) applies only in the TES Design scenario. Elements of Δ_C are the climate regulation demand for each economic sector, land use activity and biomass conversion process quantified over twenty years. As discussed in Section 3.10, the climate regulation demand consists of carbon dioxide and nitrous oxide emissions in kg CO₂-eq. Elements of Σ_C are the net climate regulation supply (supply minus demand, or sequestration minus emissions) for the same activities.

Table 9: Land used (acres), energy produced (GGE) and net present value (USD) for each energy production system component.

Component	Land Used (ac) A	Energy (GGE) E	NPV (USD) N	Unit
Cont. Corn, No Till	1	0	5.87×10^2	per acre
Cont. Corn, Conv. Till	1	0	6.67×10^2	
Corn-Soybean, No Till	1	0	3.74×10^2	
Corn-Soybean, Conv. Till	1	0	2.67×10^2	
Switchgrass, No N Fert.	1	0	-4.88×10^2	
Switchgrass, With N Fert.	1	0	-5.31×10^2	
Wind Turbine	0.1633	4.27×10^6	-3.01×10^5	per unit
Solar Panel	1.73×10^{-4}	7.9×10^1	-7.23×10^2	
White Oak	1.66×10^{-3}	0	-3.65×10^{-1}	per tree
Scots Pine	8.15×10^{-4}	0	-1.79×10^{-1}	
American Elm	1.12×10^{-3}	0	-2.47×10^{-1}	
Spruce	1.12×10^{-3}	0	-2.47×10^{-1}	
Birch	7.91×10^{-4}	0	-1.74×10^{-1}	
Eastern Hemlock	1.12×10^{-3}	0	-2.47×10^{-1}	
Corn Ethanol	—	8.02×10^7	-6.88×10^6	per plant
Soybean Biodiesel	—	5.94×10^6	2.61×10^6	
Switchgrass Ethanol*	—	8.11×10^8	-9.17×10^6	
Stover Ethanol*	—	1.18×10^9	-9.21×10^6	
Switchgrass Pyrolysis*	—	5.91×10^9	-3.17×10^6	
Stover Pyrolysis*	—	5.54×10^9	-5.96×10^6	
Switchgrass Combustion	—	1.43×10^{10}	-1.03×10^7	
Stover Combustion	—	1.97×10^{10}	-1.03×10^7	

* Includes energy and revenue from byproduct electricity

Similarly, the air quality regulation demand objective function is

$$Z_{\Delta_A} = \Delta_A \cdot \begin{bmatrix} \underline{s} \\ \underline{t} \\ \underline{s} \end{bmatrix} \quad (20)$$

and the net supply objective function is

$$Z_{\Sigma_A} = \Sigma_A \cdot \begin{bmatrix} \underline{s} \\ \underline{t} \\ \underline{s} \end{bmatrix}. \quad (21)$$

Elements of Δ_A are the air quality regulation demand quantified as nitrogen dioxide emissions; elements of Σ_A are the net air quality regulation supply. Equation (20) applies only to Life Cycle Design, and Equation (21) applies only to TES Design. $\bar{s}$ does not appear in Equations (20) and (21), as air quality regulation has a regional serviceshed. The elements of Δ_C , Δ_A , Σ_C and Σ_A are given in Table 10, for all system components except the economic sectors. Climate regulation demand values for the economic sectors may be obtained from the authors on request. [70, 71]

4 Results and discussion

A summary of the major results that highlights the comparison between Life Cycle Design and TES Design is shown in Figure 2. Optimal system designs for the ecosystem service objectives under both scenarios are shown in more detail in Figure 3, and additional ecosystem service results are shown in Figure 4. Additional detail on the results in this section is given in Annex A, and results not discussed in this section are given in Annex B.

4.1 System performance

Figure 2 summarizes the net climate regulation supply, NPV and the amount of energy produced for optimal system designs under Life Cycle Design and under TES Design. Low Energy Production and High Energy Production designs are not distinguished in Figure 2. Net air quality regulation supply is also not shown in Figure 2, but net air quality regulation supply correlates with net climate regulation supply. The text boxes in Figure 2 summarize the optimal system designs at each point, with acres of land use options and a breakdown of energy production activities.

4.1.1 Comparison between design scenarios.

TES Design and Life Cycle Design produced different optimal system designs for the ecosystem service objectives and identical designs for the energetic and NPV objectives, as expected. The TES Design scenario produced the only designs to reach absolute sustainability (green and orange triangles in Figure 2) under the maximum net ecosystem service supply objective functions. Positive net ecosystem service supplies for these designs indicates that including the forest ecosystem is sufficient to completely offset the ecosystem service demand created by the land use and energy production activities. In contrast, the minimum ecosystem service demand designs under Life Cycle Design (purple and yellow circles) are located in the lower left-hand quadrant of the graph, indicating negative net climate regulation supplies. Net air quality regulation supply, not shown in Figure 2, is also negative for these designs. Thus, under Life Cycle Design, emissions are minimized but still exceed the sequestration and pollutant removal capacity at the spatial scales considered. These results demonstrate that including both demand and supply of ecosystem services in the

Table 10: Climate regulation and air quality regulation demand and net supply for each energy production system component. Climate regulation demand at the national scale was included in both the climate regulation demand and net supply objective functions, but the demand created by each sector is not shown here.

Component	Climate Regulation (kg CO ₂ -eq)		Air Quality Regulation (kg NO ₂)		Unit
	Demand Δ_C	Net Supply Σ_C	Demand Δ_A	Net Supply Σ_A	
Cont. Corn, No Till	6.83×10^4	-6.57×10^4	2.28×10^1	-2.28×10^1	per acre
Cont. Corn, Conv. Till	7.30×10^4	-7.05×10^4	3.72×10^1	-3.72×10^1	
Corn-Soybean, No Till	6.37×10^4	-6.10×10^4	2.26×10^1	-2.26×10^1	
Corn-Soybean, Conv. Till	5.96×10^4	-5.70×10^4	3.36×10^1	-3.36×10^1	
Switchgrass, No N Fert.	5.67×10^4	-5.35×10^4	1.10×10^1	-1.10×10^1	
Switchgrass, With N Fert.	6.07×10^4	-5.75×10^4	1.28×10^1	-1.28×10^1	
Wind Turbine	0	0	0	0	per unit
Solar Panel	0	0	0	0	
White Oak	0	1.61×10^4	0	2.96	per tree
Scots Pine	0	8.65×10^3	0	2.94	
American Elm	0	1.23×10^4	0	2.96	
Spruce	0	1.31×10^4	0	2.97	
Birch	0	1.19×10^4	0	2.93	
Eastern Hemlock	0	5.24×10^3	0	3.00	
Corn Ethanol	4.30×10^7	-4.30×10^7	2.63×10^4	-2.63×10^4	per plant
Soybean Biodiesel	9.52×10^5	-9.52×10^5	2.26×10^4	-2.26×10^4	
Switchgrass Ethanol	5.00×10^6	-5.00×10^6	3.15×10^5	-3.15×10^5	
Stover Ethanol	5.32×10^6	-5.32×10^6	3.28×10^5	-3.28×10^5	
Switchgrass Pyrolysis	1.18×10^8	-1.18×10^8	1.09×10^5	-1.09×10^5	
Stover Pyrolysis	1.26×10^8	-1.26×10^8	1.16×10^5	-1.16×10^5	
Switchgrass Combustion	1.38×10^7	-1.38×10^7	7.87×10^5	-7.87×10^5	
Stover Combustion	1.50×10^7	-1.50×10^7	8.53×10^5	-8.53×10^5

Figure 2: Single-objective optimization results for both design scenarios. Text boxes contain summaries of the optimal designs for some points. The y-axis is broken at zero, with different scales above and below the dotted red line. Net air quality regulation supply is not shown, but designs with high net climate regulation supply also have high net air quality regulation supply.

objective function results in more sustainable solutions that cannot be found by the conventional approach of reducing demand.

4.1.2 Trade-off analysis.

Figure 2 shows that while trade-offs exist between the energetic, economic and ecosystem service objectives, the trade-offs are not equal between all three objectives. In particular, for the system considered, decreasing the amount of energy produced offers ecological benefits. Designs with minimum ecosystem service demand and maximum net ecosystem service supply increase in net ecosystem service supply when energy production is reduced, and this increase in sustainability is accomplished without a corresponding decrease in NPV. However, NPV cannot be increased without a significant reduction in energy production, and the designs which maximize energy production have the worst economic performance and the next-to-worst ecological performance. It is therefore possible to increase sustainability (net ecosystem service supply) without sacrificing economic performance, but not without sacrificing the amount of energy produced.

4.1.3 Existence of win-win-win designs.

None of the optimal system designs result in high NPV with high energy production and positive net ecosystem service supplies, except one design, marked as a “Compromise Design” in Figure 2. This design combines positive net ecosystem service supplies with high energy production. This design represents a compromise because the NPV is zero, thus it does not provide economic, environmental and energetic benefits simultaneously. However, the presence of more than 700 acres of reforestation in the design combined with the positive net ecosystem service supply means that the NPV can be increased by reducing the amount of reforested land until one of the net ecosystem service supplies approaches or is equal to zero. At that point, the design would have a positive NPV, be energetically productive and have absolute sustainability in both ecosystem services considered, representing a win-win-win solution.

4.2 Optimal system designs

Figure 3 shows the production system designs obtained for the ecosystem service objective functions under Life Cycle Design and under TES Design. Details on the maximum energy and maximum NPV system designs under both scenarios are given in Annex A. The results of Figure 3 confirm that TES Design and Life Cycle Design produce unique optimal designs when optimizing for ecosystem services. When optimizing climate regulation, Life Cycle Design under Low Energy Production produces a design in which relatively little land is utilized, the the dominant cropping system is no-till corn-soybean rotation and a small number of wind turbines provide the majority of the energy. TES Design under Low Energy Production, also optimizing for climate regulation, produces a design that uses the full 10,000 acres of land and combines continuous corn under conventional tillage, no-till corn-soybean rotation and a small number of wind turbines. More than half of the acreage in this design is occupied by reforestation with birch trees. The mix of energy products under TES Design is roughly the same as that under Life Cycle Design, with wind electricity once again dominating the energy products.

Results are similar when air quality regulation is optimized under Low Energy Production. Life Cycle Design produces a system in which, once again, very little of the total land is used, and the land use is dominated by a single cropping system, no-till continuous corn, with a small amount of no-till corn soybean rotation and a few wind turbines. Energy production is again dominated by wind electricity. Optimizing air quality regulation under TES Design produces the same optimal

Figure 3: System designs for ecosystem service objective functions. A fully filled-in pie chart indicates use of all 10,000 acres of land, for the land use charts, and production of the maximum amount of energy for the end product charts.

Figure 4: Ecosystem service supply, demand and sustainability index (Equation (1)) for climate regulation and air quality regulation designs. TES Design results in absolute sustainability for both ecosystem services while Life Cycle Design does not. Under TES Design, the same system design maximized the net supply of both ecosystem services.

system design as did optimizing climate regulation, with land use activities occupying the maximum amount of land and being dominated by birch tree reforestation.

Under High Energy Production, the differences between Life Cycle Design and TES Design are similar to the differences under Low Energy Production. Life Cycle Design produces systems that do not utilize the full amount of land, and the energy production is dominated by wind electricity.

Reforestation appears in every optimal system obtained under TES Design. (Under Life Cycle Design, reforestation is not permitted.) Reforestation provides only ecosystem service supply: no energetic or economic benefits result from reforestation. The presence of the reforested land allows the energy production pathways to create higher levels of demand compared to the Life Cycle Design scenario (see Figure 4 for more details), both by the use of more intensive cropping systems, such as continuous corn, conventional till, and by using a greater amount of land to produce energy. Food is also produced in each of the designs shown in Figure 3; some or all of the corn grown in each system design is sold as food rather than converted to ethanol. The sale of corn provides an additional revenue stream, which is necessary to maintain the system NPV at or above zero. Under TES Design, reforestation creates an opportunity to produce more food and the same amount of energy compared to Life Cycle Design by offsetting the additional ecosystem service demand from the more intensive corn cropping systems. These results thus demonstrate a situation in which the conventional emissions-minimizing approach leads to designs that are clearly sub-optimal.

4.3 Ecosystem service supply and demand

Figure 4 shows the ecosystem service supply, demand and net supply values for the ecosystem service system designs under Life Cycle Design and TES Design. These results confirm that system designs under TES Design reach absolute sustainability, while the Life Cycle Design scenario produces optimal designs that have close to the worst possible net ecosystem service supply values: $V_k = -1$, indicating no significant ecosystem service supply.

The TES Design scenario results in absolute sustainability (defined in Section 3.1 as $V_k \geq 1$) due to the presence of reforestation and due to the inclusion of both supply and demand in the ecosystem service objective functions. As discussed in Section 4.2, TES Design allows for systems with higher ecosystem service demand compared to Life Cycle Demand, but the additional ecosystem service supply created by reforestation is sufficient to offset the ecosystem service demand created by the agricultural and energy production activities. This is seen in Figure 4 by comparing the Life Cycle Design and TES Design results under Low Energy Production and under High Energy Production. The sustainability index values under TES Design, for both climate regulation and air quality regulation, are consistently higher than the index values under Life Cycle Design and are also consistently greater than zero. These results indicate that reducing emissions and environmental impacts alone is insufficient for a system to reach absolute sustainability.

4.4 Limitations

In this work, climate regulation demand was modeled at the national scale and the supply of climate regulation, quantified by carbon sequestration service was modeled only at the regional scale, although the largest scale applicable for climate regulation is global. This simplification was made to maintain focus on decisions at scales that can be influenced more easily by regional activities. It also helped to avoid issues related to the allocation of carbon sequestration supply at the global scale, between multiple land users. Thus the climate regulation supply provided by the land considered for energy production and ecological land use activities was alone considered. Optimal design systems that have a positive net carbon regulation supply are thus sustainable within the regional boundary considered, while systems that have a negative net regulation supply may only be sustainable by considering the ecosystem service supply at larger scales. However, consideration of supply at larger scales, through activities such as supply chain management or carbon trading, is currently ignored.

Air quality regulation in reality is dependent on several types of pollutants, including particulate matter, sulfur dioxide and ozone. Due to lack of both demand and supply data for other relevant air pollutants, only NO_2 emissions and sequestration was considered in this study.

The system model was formulated as a MILP, by simplifying and linearizing many of the component models. Fixed models were used for all biomass conversion activities, and the plant scaling was linearized to calculate the net present value of each plant. Ideally, models of the biomass conversion activities would include decision variables at the unit operation level, to simultaneously choose and optimize the biomass conversion process. While the P2P modeling framework is capable of capturing this extra level of complexity, converting the model from a MILP to a mixed-integer non-linear program (MINLP) by introducing non-linearities reduces the likelihood of finding global optima. The additional complexity from introducing non-linearities is unlikely to change the overall conclusions of this work.

To model farming activities, meteorological data had to be obtained for two different central Ohio locations, as sufficient data for either location over the twenty year period was not available. Because WinEPIC does not have the capability to model different rates of agricultural residue harvest, the amount of corn stover harvested under the continuous corn and corn-soybean rotation

cropping systems was set to a fixed fraction of the total stover produced. WinEPIC also cannot model more one soil type per farming scenario, thus the soil type over the entire 10,000 acres was assumed to be homogeneous and was chosen to be the most dominant soil type in central Ohio. Interactions between the different cropping systems were not considered, nor were interactions between the reforested land and the agricultural land. The effects of land use activities on the surrounding land that also supplies ecosystem services were also not included.

Wind turbines and solar panels were assumed to have zero ecosystem service supply and demand at the farm level. In reality these options do not create ecosystem service supply, but they are likely to affect the supply and demand created by surrounding land. For instance, grass and other plants will grow around and beneath the solar panels, providing some small amount of carbon sequestration. Some recent work has demonstrated that solar panels can also be co-located with crops, which creates more opportunities for energy production. [72] However, this option is not viable in central Ohio and was not considered in this work.

5 Conclusions and future work

The objective of this work was to develop a methodology for TES Design and demonstrate it by application to a renewable energy system, in order to demonstrate the benefits that TES Design offers over Life Cycle Design. Results show that *TES Design leads to more sustainable decisions than those obtained by Life Cycle Design*. Absolute sustainability, in which the supply of ecosystem services exceeds demand for all services considered and at the largest scale modeled, was only ever reached under TES Design. Climate regulation reached a sustainability index of 457.6 and air quality regulation reached an index of 253.5 under TES Design, while the highest index values reached under Life Cycle Design were -0.96 for climate regulation and -1 for air quality regulation (the lowest possible index value is -1). This is because Life Cycle Design results in decisions that “do less bad” by minimizing emissions, while TES Design results in decisions that also “do more good” by balancing emissions with the capacity of ecosystems to mitigate those emissions, which also encourages the restoration and protection of ecosystems.

Results also showed that trade-offs do exist between ecosystem services, energy production, and economics, but that *improving sustainability does not necessarily mean sacrificing both energy production and system economics*. When land is used for ecosystem service supply as well as energy provisioning, sustainability can be increased without sacrificing economic performance. Under TES Design, which allowed for land to be used to increase ecosystem service supply, sustainability index values were increased above zero (the value which indicates absolute sustainability) while the corresponding NPV remained at zero, the same NPV achieved by minimizing emissions under Life Cycle Design. Some amount of energy production must be sacrificed to realize the sustainability benefits, but the necessary reduction in energy production is relatively small. System designs that produced the maximum possible amount of energy had sustainability indexes of -1 for both climate regulation and air quality regulation, but system designs that produced 90% of the maximum possible amount of energy reached index values of 17.6 for climate regulation and 10.7 for air quality regulation. The NPV for the maximum energy design was zero, as was the NPV for the TES Design system producing 90% of the maximum energy. The system that maximized NPV and produced 90% of the maximum energy reached an NPV of nearly \$1 million (USD) but was still unsustainable. A second major finding from this work is therefore that *a small reduction in energy production intensity enables large benefits to be realized in either net ecosystem service supply or in system economics*. Moreover, the “compromise design” found under the TES Design scenario results demonstrates that using land for ecosystem service supply and for energy production creates an opportunity to realize energetic, economic and ecosystem service benefits simultaneously.

A general methodology for incorporating the TES concept into design applications, including guidelines on constructing and optimizing a TES model of an arbitrary system, is currently under development. The methodology will address not only building the model, but difficulties such as temporal and spatial scales associated with linked technological and ecological models.

One aspect of using land to produce energy that was not addressed in this work is water, both quantity and quality. Water use was not addressed because none of the land use options modeled required irrigation, and the biomass conversion facilities all had low water consumption due to internal recycling and wastewater treatment. Water quality, however, is an important issue for agriculture in general and Ohio in particular, as cyanobacteria blooms have degraded the quality of multiple bodies of water. Future work will include water quality regulation as a third ecosystem service. Demand is created through nitrate runoff from farmland, and supply can be provided either through the water quality regulation capacity of the surrounding watershed, or by a treatment wetland located on part of the farmland. Land taken up by the wetland will not be available for energy production, creating further competition between energy production and ecosystem service supply.

A system that co-produces food and energy is one way to mitigate the competition for land that exists between food and energy production. In this work, food production was not a focus, but the optimal system designs did in general co-produce food and energy. Work is ongoing to extend this energy production system design problem into a food-energy co-production system design problem, including competing food and energy production objectives. The extended problem will allow for the analysis of trade-offs between food production, energy production, ecosystem services and system economics. In addition to the climate and air quality regulation ecosystem services considered in this work, water quality regulation will be included as a third ecosystem service objective.

Acknowledgements

Partial financial support for this work was provided by the National Science Foundation (CBET-1336872, CBET-1404956) and the U.S. Department of Agriculture (BRDI-2012-38202-19288).

Annex A: Details on optimal systems discussed in paper

Table 11: System performance criteria for the minimum climate regulation demand designs (Life Cycle Design scenario) under low and high energy production.

		Life Cycle Design	
		Low Energy	High Energy
NPV (USD)		\$0	\$0
Energy Produced (GGE)		9,590,349	86,656,550
Climate Regulation (kg CO ₂ -eq)	Demand	69,156,229	590,435,925
	Supply	2,794,306	24,019,545
	Sustainability Index	-0.96	-0.96
Air Quality Regulation (kg NO ₂)	Demand	26,330	224,244
	Supply	0	0
	Sustainability Index	-1	-1

Table 12: System performance criteria for the minimum air quality regulation demand designs (Life Cycle Design scenario) under low and high energy production.

		Life Cycle Design	
		Low Energy	High Energy
NPV (USD)		\$0	\$0
Energy Produced (GGE)		9,590,349	86,313,141
Climate Regulation (kg CO ₂ -eq)	Demand	69,156,229	595,948,420
	Supply	2,794,306	24,066,667
	Sustainability Index	-0.96	-0.96
Air Quality Regulation (kg NO ₂)	Demand	26,330	224,155
	Supply	0	0
	Sustainability Index	-1	-1

Table 13: System performance criteria for the maximum net climate regulation supply system designs (TES Design scenario) under low and high energy production.

		TES Design	
		Low Energy	High Energy
NPV (USD)		\$0	\$0
Energy Produced (GGE)		9,590,349	86,313,141
Climate Regulation (kg CO ₂ -eq)	Demand	221,974,980	611,726,650
	Supply	101,807,608,384	11,355,156,597
	Sustainability Index	458	18
Air Quality Regulation (kg NO ₂)	Demand	98,702	239,369
	Supply	25,118,764	2,795,824
	Sustainability Index	253	11

Table 14: System performance criteria for the maximum net air quality regulation supply system designs (TES Design scenario) under low and high energy production. These designs were identical to the maximum net climate regulation supply designs.

		TES Design	
		Low Energy	High Energy
NPV (USD)		\$0	\$0
Energy Produced (GGE)		9,590,349	86,313,141
Climate Regulation (kg CO ₂ -eq)	Demand	221,974,980	611,726,650
	Supply	101,807,608,384	11,355,156,597
	Sustainability Index	458	18
Air Quality Regulation (kg NO ₂)	Demand	98,702	239,369
	Supply	25,118,764	2,795,824
	Sustainability Index	253	11

Table 15: Minimum air quality regulation demand, Life Cycle Design, Low Energy Production

Component	Amount	Units
Cont. Corn, No Till	0	acres
Cont. Corn, Conv. Till	0	
Corn-Soybean, No Till	1,049	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	2	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	0	
Eastern Hemlock	0	
Unused Land	8,950	acres
Wind Electricity	8,537,689	GGE
Solar Electricity	0	
Corn Grain Ethanol	407,175	
Soybean Biodiesel	662,799	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol Ethanol	0	
Stover Ethanol Electricity	0	
	0	
Switchgrass Pyrolysis Gasoline	0	
Switchgrass Pyrolysis Electricity	0	
	0	
Stover Pyrolysis Gasoline	0	
Stover Pyrolysis Electricity	0	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	18,959	million food calories
Soybeans	0	

Table 16: Minimum climate regulation demand, Life Cycle Design, Low Energy Production. This design is identical to the minimum air quality regulation demand design under Life Cycle Design and Low Energy Production, Table 15.

Component		Amount	Units
Cont. Corn, No Till		0	acres
Cont. Corn, Conv. Till		0	
Corn-Soybean, No Till		1,049	
Corn-Soybean, Conv. Till		0	
Switchgrass, With N Fert.		0	
Switchgrass, No N Fert.		0	
Wind Turbines		2	turbines
Solar Panels		0	panels
White Oak		0	acres
Scots Pine		0	
American Elm		0	
Spruce		0	
Birch		0	
Eastern Hemlock		0	
Unused Land		8,950	acres
Wind Electricity		8,537,689	GGE
Solar Electricity		0	
Corn Grain Ethanol		407,175	
Soybean Biodiesel		662,799	
Switchgrass Ethanol	Ethanol	0	
Switchgrass Ethanol	Electricity	0	
Stover Ethanol	Ethanol	0	
	Electricity	0	
	Diesel	0	
Switchgrass Pyrolysis	Gasoline	0	
	Electricity	0	
	Diesel	0	
Stover Pyrolysis	Gasoline	0	
	Electricity	0	
Switchgrass Combustion	Electricity	0	
Stover Combustion	Electricity	0	
Corn Grain		18,959	million food calories
Soybeans		0	

Table 17: Minimum air quality regulation system design, Life Cycle Design, High Energy Production

Component	Amount	Units
Cont. Corn, No Till	603	acres
Cont. Corn, Conv. Till	0	
Corn-Soybean, No Till	8,462	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	19	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	0	
Eastern Hemlock	0	
Unused Land	931	acres
Wind Electricity	81,108,047	GGE
Solar Electricity	0	
Corn Grain Ethanol	0	
Soybean Biodiesel	5,344,723	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol	Ethanol	
	Electricity	
	Diesel	
Switchgrass Pyrolysis	Gasoline	
	Electricity	
	Diesel	
Stover Pyrolysis	Gasoline	
	Electricity	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	219,984	million food calories
Soybeans	0	

Table 18: Minimum climate regulation demand design, Life Cycle Design, High Energy Production.

Component		Amount	Units
Cont. Corn, No Till		0	acres
Cont. Corn, Conv. Till		0	
Corn-Soybean, No Till		9,020	
Corn-Soybean, Conv. Till		0	
Switchgrass, With N Fert.		0	
Switchgrass, No N Fert.		0	
Wind Turbines		19	turbines
Solar Panels		0	panels
White Oak		0	acres
Scots Pine		0	
American Elm		0	
Spruce		0	
Birch		0	
Eastern Hemlock		0	
Unused Land		977	acres
Wind Electricity		81,108,047	GGE
Solar Electricity		0	
Corn Grain Ethanol		0	
Soybean Biodiesel		5,697,345	
Switchgrass Ethanol	Ethanol	0	
Switchgrass Ethanol	Electricity	0	
Stover Ethanol	Ethanol	0	
	Electricity	0	
	Diesel	0	
Switchgrass Pyrolysis	Gasoline	0	
	Electricity	0	
	Diesel	0	
Stover Pyrolysis	Gasoline	0	
	Electricity	0	
Switchgrass Combustion	Electricity	0	
Stover Combustion	Electricity	0	
Corn Grain		202,451	million food calories
Soybeans		0	

Table 19: Maximum net air quality regulation supply system design, TES Design, Low Energy Production.

Component	Amount	Units	
Cont. Corn, No Till	0	acres	
Cont. Corn, Conv. Till	1,511		
Corn-Soybean, No Till	1,711		
Corn-Soybean, Conv. Till	0		
Switchgrass, With N Fert.	0		
Switchgrass, No N Fert.	0		
Wind Turbines	2	turbines	
Solar Panels	0	panels	
White Oak	0	acres	
Scots Pine	0		
American Elm	0		
Spruce	0		
Birch	6,777		
Eastern Hemlock	0		
Unused Land	0	acres	
Wind Electricity	8,537,689	GGE	
Solar Electricity	0		
Corn Grain Ethanol	0		
Soybean Biodiesel	1,080,898		
Switchgrass Ethanol Ethanol	0		
Switchgrass Ethanol Electricity	0		
Stover Ethanol Ethanol	0		
Stover Ethanol Electricity	0		
	Diesel		0
Switchgrass Pyrolysis Gasoline	0		
	Electricity		0
	Diesel		0
Stover Pyrolysis Gasoline	0		
	Electricity		0
Switchgrass Combustion Electricity	0		
Stover Combustion Electricity	0		
Corn Grain	111,310	million food calories	
Soybeans	0		

Table 20: Maximum net climate regulation supply system design, TES Design, Low Energy Production. This design is identical to the maximum net air quality regulation supply design under Low Energy Production, Table 19.

Component	Amount	Units	
Cont. Corn, No Till	0	acres	
Cont. Corn, Conv. Till	1,511		
Corn-Soybean, No Till	1,711		
Corn-Soybean, Conv. Till	0		
Switchgrass, With N Fert.	0		
Switchgrass, No N Fert.	0		
Wind Turbines	2	turbines	
Solar Panels	0	panels	
White Oak	0	acres	
Scots Pine	0		
American Elm	0		
Spruce	0		
Birch	6,777		
Eastern Hemlock	0		
Unused Land	0	acres	
Wind Electricity	8,537,689	GGE	
Solar Electricity	0		
Corn Grain Ethanol	0		
Soybean Biodiesel	1,080,898		
Switchgrass Ethanol Ethanol	0		
Switchgrass Ethanol Electricity	0		
Stover Ethanol	Ethanol		0
	Electricity		0
	Diesel		0
Switchgrass Pyrolysis	Gasoline		0
	Electricity		0
	Diesel		0
Stover Pyrolysis	Gasoline		0
	Electricity		0
Switchgrass Combustion Electricity	0		
Stover Combustion Electricity	0		
Corn Grain	111,310	million food calories	
Soybeans	0		

Table 21: Maximum net air quality regulation supply system design, TES Design, High Energy Production.

Component	Amount	Units
Cont. Corn, No Till	0	acres
Cont. Corn, Conv. Till	780	
Corn-Soybean, No Till	8,462	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	19	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	754	
Eastern Hemlock	0	
Unused Land	0	acres
Wind Electricity	81,108,047	GGE
Solar Electricity	0	
Corn Grain Ethanol	0	
Soybean Biodiesel	5,344,723	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol	Ethanol	
	Electricity	
	Diesel	
Switchgrass Pyrolysis	Gasoline	
	Electricity	
	Diesel	
Stover Pyrolysis	Gasoline	
	Electricity	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	227,571	million food calories
Soybeans	0	

Table 22: Maximum net climate regulation supply system design, TES Design, High Energy Production. This design is identical to the maximum net air quality regulation supply system design under High Energy Production, Table 21.

Component	Amount	Units	
Cont. Corn, No Till	0	acres	
Cont. Corn, Conv. Till	780		
Corn-Soybean, No Till	8,462		
Corn-Soybean, Conv. Till	0		
Switchgrass, With N Fert.	0		
Switchgrass, No N Fert.	0		
Wind Turbines	19	turbines	
Solar Panels	0	panels	
White Oak	0	acres	
Scots Pine	0		
American Elm	0		
Spruce	0		
Birch	754		
Eastern Hemlock	0		
Unused Land	0	acres	
Wind Electricity	81,108,047	GGE	
Solar Electricity	0		
Corn Grain Ethanol	0		
Soybean Biodiesel	5,344,723		
Switchgrass Ethanol Ethanol	0		
Switchgrass Ethanol Electricity	0		
Stover Ethanol Ethanol	0		
Stover Ethanol Electricity	0		
	Diesel		0
Switchgrass Pyrolysis Gasoline	0		
Switchgrass Pyrolysis Electricity	0		
	Diesel		0
Stover Pyrolysis Gasoline	0		
Stover Pyrolysis Electricity	0		
Switchgrass Combustion Electricity	0		
Stover Combustion Electricity	0		
Corn Grain	227,571	million food calories	
Soybeans	0		

Annex B: Details on additional optimal systems not discussed in paper

Table 23: System performance criteria for the maximum NPV system designs under both design scenarios and energy production constraints.

	Life Cycle Design		TES Design	
	Low Energy	High Energy	Low Energy	High Energy
NPV (USD)	\$6,091,024	\$669,064	\$6,091,024	\$669,064
Energy Produced (GGE)	9,590,349	86,313,141	9,590,349	86,313,141
Demand	656,156,835	667,027,915	656,156,834	667,027,915
Climate Regulation (kg CO ₂ -eq)	26,376,668	26,334,162	26,376,668	26,334,162
Supply Sustainability Index	-0.96	-0.96	-0.96	-0.96
Demand	265,180	267,399	265,180	267,399
Air Quality Regulation (kg NO ₂)	0	0	0	0
Supply Sustainability Index	-1	-1	-1	-1

Table 24: System performance criteria for the maximum energy system design, which was identical under both design scenarios and energy production constraints.

	Life Cycle Design		TES Design	
	Low Energy	High Energy	Low Energy	High Energy
NPV (USD)	\$0	\$0	\$0	\$0
Energy Produced (GGE)	95,903,490	95,903,490	95,903,490	95,903,490
Demand	654,458,620	654,458,620	654,458,620	654,458,620
Supply	26,618,967	26,618,967	26,618,967	26,618,967
Sustainability Index	-0.96	-0.96	-0.96	-0.96
Demand	248,577	248,577	248,577	248,577
Supply	0	0	0	0
Sustainability Index	-1	-1	-1	-1

Table 25: Maximum energy system design. The maximum energy design remained the same under both design scenarios and under both energy production constraints.

Component		Amount	Units
Cont. Corn, No Till		0	acres
Cont. Corn, Conv. Till		0	
Corn-Soybean, No Till		9,997	
Corn-Soybean, Conv. Till		0	
Switchgrass, With N Fert.		0	
Switchgrass, No N Fert.		0	
Wind Turbines		21	turbines
Solar Panels		0	panels
White Oak		0	acres
Scots Pine		0	
American Elm		0	
Spruce		0	
Birch		0	
Eastern Hemlock		0	
Unused Land		0	acres
Wind Electricity		89,645,737	GGE
Solar Electricity		0	
Corn Grain Ethanol		108,785	
Soybean Biodiesel		6,313,918	
Switchgrass Ethanol	Ethanol	0	
Switchgrass Ethanol	Electricity	0	
Stover Ethanol	Ethanol	0	
	Electricity	0	
	Diesel	0	
Switchgrass Pyrolysis	Gasoline	0	
	Electricity	0	
	Diesel	0	
Stover Pyrolysis	Gasoline	0	
	Electricity	0	
Switchgrass Combustion	Electricity	0	
Stover Combustion	Electricity	0	
Corn Grain		223,133	million food calories
Soybeans		0	

Table 26: Maximum NPV, Life Cycle Design, Low Energy Production

Component	Amount	Units
Cont. Corn, No Till	0	acres
Cont. Corn, Conv. Till	1,348	
Corn-Soybean, No Till	8,651	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	1	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	0	
Eastern Hemlock	0	
Unused Land	0	acres
Wind Electricity	0	GGE
Solar Electricity	0	
Corn Grain Ethanol	5,344,723	
Soybean Biodiesel	0	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol	Ethanol	
	Electricity	
	Diesel	
Switchgrass Pyrolysis	Gasoline	
	Electricity	
	Diesel	
Stover Pyrolysis	Gasoline	
	Electricity	
	Diesel	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	263,958	million food calories
Soybeans	0	

Table 27: Maximum NPV system design, Life Cycle Design, High Energy Production.

Component	Amount	Units
Cont. Corn, No Till	0	acres
Cont. Corn, Conv. Till	1,535	
Corn-Soybean, No Till	8,462	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	19	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	0	
Eastern Hemlock	0	
Unused Land	0	acres
Wind Electricity	81,108,047	GGE
Solar Electricity	0	
Corn Grain Ethanol	0	
Soybean Biodiesel	5,344,723	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol Ethanol	0	
Stover Ethanol Electricity	0	
Stover Ethanol Diesel	0	
Switchgrass Pyrolysis Gasoline	0	
Switchgrass Pyrolysis Electricity	0	
Switchgrass Pyrolysis Diesel	0	
Stover Pyrolysis Gasoline	0	
Stover Pyrolysis Electricity	0	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	263,958	million food calories
Soybeans	0	

Table 28: Maximum NPV system design, TES Design, Low Energy Production.

Component	Amount	Units
Cont. Corn, No Till	0	acres
Cont. Corn, Conv. Till	1,348	
Corn-Soybean, No Till	8,651	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	1	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	0	
Eastern Hemlock	0	
Unused Land	0	acres
Wind Electricity	4,268,845	GGE
Solar Electricity	0	
Corn Grain Ethanol	0	
Soybean Biodiesel	5,464,257	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol Ethanol	0	
Stover Ethanol Electricity	0	
	0	
Switchgrass Pyrolysis Gasoline	0	
Switchgrass Pyrolysis Electricity	0	
	0	
Stover Pyrolysis Gasoline	0	
Stover Pyrolysis Electricity	0	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	259,218	million food calories
Soybeans	0	

Table 29: Maximum NPV system design, TES Design, High Energy Production. This design is identical to the maximum NPV design under Life Cycle Design and High Energy Production, Table 27.

Component	Amount	Units
Cont. Corn, No Till	0	acres
Cont. Corn, Conv. Till	1,535	
Corn-Soybean, No Till	8,462	
Corn-Soybean, Conv. Till	0	
Switchgrass, With N Fert.	0	
Switchgrass, No N Fert.	0	
Wind Turbines	19	turbines
Solar Panels	0	panels
White Oak	0	acres
Scots Pine	0	
American Elm	0	
Spruce	0	
Birch	0	
Eastern Hemlock	0	
Unused Land	0	acres
Wind Electricity	81,108,047	GGE
Solar Electricity	0	
Corn Grain Ethanol	0	
Soybean Biodiesel	5,344,723	
Switchgrass Ethanol Ethanol	0	
Switchgrass Ethanol Electricity	0	
Stover Ethanol Ethanol	0	
Stover Ethanol Electricity	0	
Stover Ethanol Diesel	0	
Switchgrass Pyrolysis Gasoline	0	
Switchgrass Pyrolysis Electricity	0	
Switchgrass Pyrolysis Diesel	0	
Stover Pyrolysis Gasoline	0	
Stover Pyrolysis Electricity	0	
Switchgrass Combustion Electricity	0	
Stover Combustion Electricity	0	
Corn Grain	263,958	million food calories
Soybeans	0	

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