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

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highlights

- Existing methods for sustainable systems design improve relative sustainability only.
- The TES Design methodology is capable of achieving absolute sustainability.
- TES Design is demonstrated by application to a renewable energy production system.
- Results show that TES Design achieves sustainable, economical, productive systems.

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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.

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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 outstrip 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 disservices. 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 also needs to 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 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 include 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
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