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A system of systems approach to energy sustainability assessment: Are all renewables really green?

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ABSTRACT

Renewable energies are emerging across the globe in an attempt to slow down global warming and to improve national energy security in face of the depleting fossil fuel reserves. However, the general policy of mandating the replacement of fossil fuels with the so-called "green" energies may not be as effective and environmental-friendly as previously thought, due to the secondary impacts of renewable energies on different natural resources. Thus, an integrated systems analysis framework is essential to selecting optimal energy sources that address global warming and energy security issues with minimal unintended consequences and undesired secondary impacts on valuable natural resources. This paper proposes a system of systems (SoS) framework to determine the relative aggregate footprint (RAF) of energy supply alternatives with respect to different sustainability criteria and uncertain performance values. Based on the proposed method, the RAF scores of a range of renewable and nonrenewable energy alternatives are determined using their previously reported performance values under four sustainability criteria, namely carbon footprint, water footprint, land footprint, and cost of energy production. These criteria represent environmental efficiency, water use efficiency, land use efficiency, and economic efficiency, respectively. The study results suggest that geothermal energy and biomass energy from miscanthus are the most and least resource-use efficient energy alternatives based on the performance data available in the literature. In addition, despite their lower carbon footprints, some renewable energy sources are less promising than non-renewable energy sources from a SoS perspective that considers the trade-offs between the greenhouse gas emissions of energies and their effects on water, ecosystem, and economic resources. Robustness analysis suggests that with respect to the existing performance values and uncertainties in the literature, solar thermal and hydropower have the most and least level of RAF robustness, respectively. Sensitivity analysis indicates that geothermal energy and ethanol from sugarcane, have the lowest and highest RAF sensitivity to resource availability, respectively.

1. Introduction

Conventional fossil fuels, including oil, coal, and natural gas, have been the major sources of energy production worldwide. These fossil fuels, however, are becoming increasingly inaccessible in terms of extraction as new reserves become harder to find. Most areas around the world have no access to sufficient fossil energy reserves and, consequently, must meet their demands through energy imports. This makes national energy supply plans uncertain and insecure, due to unreliability of fossil energy availability, which can be affected by different factors, including political stability, economic conditions, regulations, and national development plans of fossil fuel suppliers. Also, powerful players of the energy market such as OPEC members could affect the global energy security through their future energy production policies (Mirchi et al., 2012) due to the high dependency of current energy systems on the limited fossil fuel resources (UNEP, 2011).

Global warming, due to increasing greenhouse gas (GHG) emissions from burning fossil fuels, has been recognized as one of the major obstacles to sustainable planning and development (CIEL, 2002; McDonald, 2006; USAID, 2011). Climate warming is expected to create a range of issues, including but not limited to health and environmental problems (EPA, 2011; NRDC, 2011), rising sea levels (NCDC, 2011), changing rainfall and temperature patterns (Dore, 2005; Mirchi et al., 2013), manipulated ecosystem productivity (Doll and Zhang, 2010), agricultural productivity deterioration (Gohari et al., 2013a; Msowoya et al., 2014), increased energy

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demand and prices (Guégan et al., 2012), and limited availability of water-dependent energy sources such as hydropower (Jamali et al., 2013; Madani et al., 2014a).

Many countries around the world have been developing policies in an attempt to preserve their national energy security and to adapt to climate change. The emerging policies are mostly inclined to use more renewables in the future, so the ideal future energy supply portfolios include a combination of both fossil fuels and renewables, with the share of the renewables increasing gradually over time. For example, in the U.S., different states have renewable portfolio standards or goals (Zonis, 2011) that mandate certain levels of energy supply from renewables in the near future; in their 20/20/20 energy strategy, the European Union (EU) has set an overall mandatory target of 20% for the portion of renewable energy in the gross domestic consumption by 2020 (EU, 2011); Denmark aims to cover 50% and 100% of the electricity demand through renewables by 2020 and 2050, respectively (The Danish Government, 2012); Scotland plans to fully satisfy electricity demand via renewables by 2020 (The Scottish Government, 2012); and Germany pursues the 80% renewable electricity target by 2050 (Klaus et al., 2010).

Sustainable development mandates establishing a balance between biocapacity and ecological footprint. The former represents the area of productive land and water available to produce resources and absorb carbon dioxide wastes, while the latter reflects the area of productive land and water required to produce resources and absorb carbon dioxide wastes. The global ecological footprint exceeded the world's biocapacity by 44% in 2006 and is expected to surpass it by 100% in late 2030s, as a result of population growth and economic development, associated with increased consumption of goods/services and natural resource exhaustion (Global Footprint Network, 2010). Continuation of this trend leads to natural resources unsustainability and eventually to ecosystem collapse (Holmberg et al., 1999; Wackernagel et al., 2002; Foley et al., 2005; UN, 2005).

In comparison with fossil energy sources, the renewable energies can be continually replenished. They are known to be more environmental-friendly and 'green' as they are expected to produce less carbon dioxide and other greenhouse gases. This has been the significant motivation for proposing the immediate substitution of fossil fuels with renewables to mitigate global warming. Nevertheless, what largely ignored by such substitution policies are the unintended consequences emerging from the increased use of renewables, especially with respect to their effects on other valuable natural resources (e.g., water and land) in the long run. Some renewable energy sources, such as hydropower and biomass, affect water more than the others. Additionally, the production of some energy sources like ethanol and biomass requires large land areas. These secondary impacts on water and land can establish barriers to sustainable development as the pressure on a major component of the ecosystem (e.g., land, water) can eventually yield to the failure of that component and even to the collapse of the whole system due to the strong interrelations of ecosystem components.

Moving toward a sustainable future requires policy actions that solve existing problems without creating new ones (Gohari et al., 2013b; Hjorth and Madani, 2014). It is essential to consider the byproducts of our global warming solutions, affecting other valuable natural resources. In case of renewable energies, it is unjustifiable to invest in an energy production method that produces minimal GHGs, yet demands considerable amounts of natural resources (e.g. water and/or land) and/or significant financial backup in the long run. Although active use of renewable energies might be effective in reducing greenhouse gas emissions and mitigating global warming effects, secondary impacts on the other components of the ecosystem, namely water and land, are inevitable if carbon footprint is the only decision driver. As a result, the general policy of substituting fossil fuels with renewables might perform effectively in solving the existing problems, unless the other aspects of this policy are also taken into consideration. Ultimately, there is no alternative other than replacing the conventional energy sources with renewables, as the current world's energy supply profile is unsustainable in terms of energy security and environmental impacts. However, tradeoffs should be seriously considered and the secondary impacts on other natural resources should be minimized to avoid irreversible ecosystem damages.

Assessment of the sustainability of energy sources must be done through a hierarchical systems procedure that minimizes the impacts of energy production on each complex resource system (lower level consideration) with respect to the trade-offs involved and the aggregate impacts (higher level consideration). Because we are dealing with a large system which itself is composed of independent but interacting systems (water, land, climate, economy, etc.), the hierarchical sustainability assessment procedure can be best developed within a system of systems (SoS) framework (Hipel et al., 2008; Phillis et al., 2010; Hjorth and Madani, 2014). So, the objective of this paper is to develop a quantitative procedure within the SoS framework (Ackoff, 1971) to evaluate the desirability of different energy sources with respect to sustainability concerns. A new footprint index, namely the relative aggregate footprint (RAF), is proposed which can be used to evaluate the aggregate impact of energy sources on different resources systems considering the existing uncertainties in their estimated impacts. Simply put, the RAF index integrates different footprint indicators in an attempt to provide a deeper understanding of the overall negative impacts of energy production processes. This index does not have some of the limitations of prior footprint concepts that result in misjudgments based on disintegrated analysis of environmental impacts, poor understanding of the involved trade-offs, and neglected effects of the information uncertainties. The value of RAF index is calculated for each energy to indicate how a holistic view of energy production impacts can change the desirability of some of the so-called 'green' energy sources.

2. Method

2.1. Energy production impacts: Selecting lower level indicators

As mentioned, energy production processes have several economic, environmental, and social impacts that should be scrutinized for development of reliable and sustainable energy policies. Examples of such impacts are the water footprint, land footprint, and cost of energy production activities. These indicators, each quantifying the effects of energy production life cycle on a given resource (i.e. water, land/ecosystem and economy) along with the carbon footprint of different energy sources have been chosen as the impact analysis criteria in this study.

One of the most notable secondary effects of the energy production processes is water resources depletion. Energy is required for extraction, treatment, and distribution of water and water is needed to produce energy (Dennen et al., 2007; Hadian and Madani, 2013). While the available water becomes more limited, by 2035, the global water demand of the energy sector is expected to grow by 37–66% compared to 2012 (Hadian and Madani, 2013). Introduction of some renewable energies to substitute conventional fossil energies can create competition over water (Gerbens-Leenes et al., 2007), especially among the food and energy sectors with the potential to increase food prices and decrease food security (Gerbens-Leenes and Hoekstra, 2011a). Some renewable energy sources require significantly high amounts of freshwater. When water consumption is considered as a sustainability criterion, these energy sources become inefficient and unreliable in comparison to some traditional sources with low water use intensity. For example, the amount of water used or affected during the production one