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.

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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...
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; Phillips 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
unit of some bioenergies is between 70 and 400 times larger than the water used or affected to produce energy from the conventional fossil energy sources (Gerbens-Leenes et al., 2009a). A significant amount of freshwater (estimated to be 68 m\(^3\)/GJ by Mekonnen and Hoekstra (2012)) is lost through evaporation for generating hydroelectricity, the most prevalent renewable energy source. Other renewable energy technologies also show a large variability in direct and indirect water consumptions (Spang, 2012).

Decarbonizing the current energy systems may be the most important step in climate change mitigation, but excluding the water-energy nexus in energy policy evaluations results in unsustainable solutions to climate change that create other issues such as water shortage. Given the important role of water resources in sustainable development and considering the fact that nearly half of the world’s population will be living in conditions of severe water stress by 2030 (OECD, 2011), the water use efficiency of energy sources must be taken into account in energy efficiency analyses and sustainable energy planning (Hadian and Madani, 2013). This is particularly important for countries with high water usage such as the U.S. with an average per capita water footprint of 2842 cubic meters per year – 105% more than the world’s average water footprint (Mekonnen and Hoekstra, 2011a).

Water footprint, defined as the total amount of freshwater used to produce different products (here, energies) (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2007, 2008), is a reliable metric for evaluating water use efficiency. Water footprint of different products and services including energy sources, energy applications, and energy utilization modes have been explored in previous studies. Gleick (1994) calculated the consumptive water use of energy production for different energy sources and concluded that energy planning is highly dependent on the available regional water resources. King et al. (2008a) studied the significance of water use in power generations and reported that the thermoelectric power plants in the U.S., which provided 91% of total electricity supply in 2007, were responsible for 40% of the U.S. freshwater withdrawals for cooling purposes. Gerbens-Leenes and Hoekstra (2011a) studied water footprints of different modes of transport based on first generation biomass, bio-ethanol and bio-electricity, and concluded that electricity is much more efficient than biofuels in terms of water footprint. Gerbens-Leenes et al. (2009a) calculated the water footprint of energy from biomass for fifteen crops, emphasizing that the large difference between the average water footprint of biomass and the average water footprint of primary energy carriers makes bioenergies inefficient in terms of water use. Mekonnen and Hoekstra (2012) estimated the blue water footprint (the volume of surface and ground water consumed in the energy production process) of electricity from hydropower for a number of hydropower plants to be equivalent to 10% of global blue water footprint of crop production, concluding that hydropower is a significant water consumer. Hadian and Madani (2013) estimated the water footprint of present and future global energy mixes, concluding that average water footprint per unit of energy production increases by 5–10% in the next two decades as a result of the increasing share of renewables in the energy supply portfolios. Other studies of water use of energy sources include Gerbens-Leenes et al. (2008, 2009b), Twomey et al. (2010), Mekonnen and Hoekstra (2010, 2011b,c), Gerbens-Leenes and Hoekstra (2011b), Stillwell et al. (2011), and Fader et al. (2011). Table 1 shows the water footprint of different energy sources based on the existing information in the literature. It must be noted that the value ranges in Table 1 account for variation and uncertainty in performances of energy production technologies under different conditions around the world. Thus, these values can vary significantly based on regional dynamics.

Similar to water, as one of the principal ecosystem components, land plays a significant role in maintaining a balanced ecosystem state and if deteriorated, can endanger ecologic sustainability (Burkhart et al., 2012; Helfenstein and Kienast, 2014). Examples of negative land use impacts on the ecosystem include ecosystem productivity degradation (Vitousek et al., 1997), biodiversity loss (Pimm and Raven, 2000), soil erosion (Miller and Tidman, 2001), carbon cycle disruption and climate change (Houghton and Hackler, 2002; Pielke et al., 2002), and water quality deterioration (Matson et al., 1997; Bennet et al., 2001). Improving energy production/use efficiency and energy conservation can decrease the land footprint of energy through reducing the need for additional land for energy production (Outka, 2011). Thus, similar to the water-energy nexus, the land-energy nexus must be considered in developing sustainable energy plans as energy plans affect land use and the global ecological footprint. Some energy sources such as nuclear have comparatively small land footprints, while others, such as biomass and ethanol, have large land footprints when compared to others.

Land use practices are highly affected by the energy life cycle and travel distances between different energy production/transportation steps. Similarly, energy production can be influenced by land use conditions. For example, energy crops require arable land, creating a competition between energy and food crops with significant implications for food prices (Dale et al., 2011). Satisfying the U.S. 2005 electricity demand via wind power, would need an area equal to the combined area of Texas and Louisiana. Using biofuels to generate the same amount of energy that can be produced by a 1000 MW nuclear powerplant would require 2500 square kilometers of land (Ausubel, 2007).

Recognizing land use as another energy sustainability criterion might make some energy production options inefficient and unsustainable. In its 20/20/20 energy policy, for instance, the European Union (EU) determined a minimum energy supply share of 10% for biofuels in 2020 (EU, 2011). In the U.S., according to the Energy Independence and Security Act of 2007, 136 billion liters (36 billion gallons) of biofuel from corn and cellulosic crops should be produced in 2022 (Pimentel et al., 2009). According to a study by Shell (2008), a 20% increase in the usage of biomass as an energy source is expected by 2050, accounting for 15% of the total energy use. This is despite the fact that given the significant land use impacts of biofuels, their sustainability as a solution to global warming is questionable. A number of studies have been focusing on the land use intensity of energy sources, including McDonalds et al. (2009), Fthenakis and Kim (2009), and Lovins (2011). Table 1 shows the values for the land footprint of different energy sources, defined as the direct and indirect area of land used for energy production purposes (Lugschitz et al., 2011).

Economics of energy is an important non-environmental criterion that highly influences energy planning. Cost of energy production/supply becomes more significant in face of growing energy prices at the global scale as the energy suppliers seek maximizing their profit through cheaper energy production methods. Several studies have explored the cost of energy production from different sources. Energy production cost is normally expressed as levelized cost, reflecting the capital costs, fuel costs, fixed and variable operation and maintenance costs, finance costs, and the utilization rate for each plant type (ICCEPT, 2002; Cosijns and D’haeseleer, 2007; Lazard, 2009: EPRI, 2011; EIA, 2011a). Table 1 shows the levelized cost of different energy sources.

Life cycle-based energy production impact indicators such as levelized cost, carbon footprint, water footprint, and land footprint provide invaluable information about the effects of energy production on different interacting systems (economy, climate, water, and land) within a coupled human–natural SoS. Nevertheless, individually, such indices fail to provide sufficient information for evaluating the overall footprint of energy sources and their sustainability. Thus, a SoS perspective (Fig. 1) is required to develop a holistic understanding of the aggregate effects of energy sources on the larger human–natural system. Indeed, the
Table 1 indicates the average global-scale performances of different energy sources under the four lower level criteria considered in this study. The provided information is based on an extensive review of the information in the literature. Some of the table values are given in intervals, reflecting the uncertainties involved in the energy performances due to technological, geographic, geologic, and other variations at the global scale. The carbon footprint values are based on life cycle assessment (LCA) studies, which take into account emissions during the life cycle of the energy production. The values for water footprint reflect the water used and impacted during different production phases to produce energy. Where data were taken from different sources, the values were checked for consistency with respect to different assumptions behind the estimations in each study. The levelized cost values for different energy sources in this study are primarily chosen from ICCEPT (2002) and Cosijns and D’haeseleer (2007). Given the assumptions used in these studies, their numbers are more applicable globally than at a regional basis. In order to account for the uncertainties involved in the long term cost estimations, the ranges used in this study are based on the interest rate used in the original studies (10%). It is also assumed that all technologies become mature after 2020; so, the levelized cost of one unit of energy from different sources becomes almost constant over a long period. Extracted cost data from different studies were adjusted for the differences between the relevant currencies and the year of calculation. The euro to dollar conversion rate was assumed to be 1.30 $/€. The levelized cost of electricity from various biomass and ethanol sources were assumed to be the same.

Table 1: Carbon footprint, water footprint, land footprint, and cost of different energy sources.

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Carbon footprint (g CO₂/kWh)</th>
<th>Water footprint (m³/GJ)</th>
<th>Land footprint (m²/GWh)</th>
<th>Cost (cents/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol from corn</td>
<td>81–85 (Hill et al., 2006)</td>
<td>78 (Gerbens-Leenes et al., 2009a)</td>
<td>10667–12500 (McDonalds et al., 2009)</td>
<td>2–4 (ICCEPT, 2002)</td>
</tr>
<tr>
<td>Ethanol from sugar cane</td>
<td>19 (Oliveira, 2008)</td>
<td>99 (Gerbens-Leenes et al., 2009b)</td>
<td>9520 (McDonalds et al., 2009)</td>
<td>2–4 (ICCEPT, 2002)</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>8.5–11.3 (Jacobson, 2009)</td>
<td>0.037–0.780 (Jacobson, 2009)</td>
<td>340–680 (McDonalds et al., 2009)</td>
<td>4–10 (ICCEPT, 2002)</td>
</tr>
<tr>
<td>Wave and tidal</td>
<td>14–119 (Jacobson, 2009)</td>
<td>0.001 (Jacobson, 2009)</td>
<td>22 (Gerbens-Leenes et al., 2009a)</td>
<td>33–463 (McDonalds et al., 2009)</td>
</tr>
<tr>
<td>Hydropower</td>
<td>2–48 (NEI, 2012b)</td>
<td>22 (Gerbens-Leenes et al., 2009a)</td>
<td>33–463 (McDonalds et al., 2009)</td>
<td>5–15 (ICCEPT, 2002)</td>
</tr>
<tr>
<td>Coal</td>
<td>834–1026 (World Energy Council, 2004)</td>
<td>0.15–0.58 (Hill and Younos, 2007)</td>
<td>83–567 (McDonalds et al., 2009)</td>
<td>3.25–12.35 (Commission of European Communities, 2007)</td>
</tr>
<tr>
<td>Nuclear</td>
<td>9–70 (Jacobson, 2009)</td>
<td>0.42–0.76 (Jacobson, 2009)</td>
<td>63–93 (McDonalds et al., 2009)</td>
<td>4.56–11.96 (Cosijns and D’haeseleer, 2007)</td>
</tr>
<tr>
<td>Geothermal</td>
<td>15.1–55 (Jacobson, 2009)</td>
<td>0.005 (Jacobson, 2009)</td>
<td>33–463 (McDonalds et al., 2009)</td>
<td>4.55–5.46 (Cosijns and D’haeseleer, 2007)</td>
</tr>
</tbody>
</table>

* Assumed to be the same as biomass woodchip.

Fig. 1. Energy sustainability assessment within a system of systems framework.
2.2. Energy RAF (relative aggregate footprint)

In essence, the complexity of energy planning resulting from social, political, technological, economic, and ecosystem interactions requires a system of multiple criteria/objectives that should be evaluated and included in energy policy making. A systems approach to energy planning has been encouraged in several studies. Sims et al. (2003) analyzed the efficiency of different energy sources for their economic and carbon mitigation potential and concluded that nuclear, wind, hydropower and bioenergy technologies are efficient, while solar and carbon sequestration technologies are not. The World Energy Council (2004) compared energy systems using the LCA method, emphasizing the importance of considering different criteria in energy systems analysis, such as energy accessibility (representing costs of energy), energy availability (representing reliability of energy), and energy acceptability (representing environmental impacts). This study concluded that emissions from renewables and nuclear energy are comparable, while environmental impacts of fossil fuels could be decreased significantly if advanced technologies are applied. Abulfotuh (2007) while environmental impacts of fossil fuels could be decreased significantly if advanced technologies are applied. Abulfotuh (2007) emphasized the importance of considering the links between energy use, economic growth, and the environmental impacts of the excessive use of energy in energy and environmental problems. Wang et al. (2009) reviewed the literature on Multi-Criteria Decision-Making (MCDM) applications in sustainable energy planning and concluded that efficiency, investment cost, CO2 emissions and job creation criteria, associated with technical, economic, environmental and social attributes, have been the main focus of previous research. Zhao et al. (2009) evaluated various power supply technologies based on the Analytic Hierarchy Process (AHP) and concluded that from a sustainability perspective, hydropower and solar power are the best and the worst alternatives, respectively. Jacobson (2009) reviewed the possible solutions to global warming, air pollution, and energy security, taking into account the unintended effects on water supply, land use, wildlife, resource availability, thermal pollution, water chemical pollution, nuclear proliferation, and under-nutrition. He ranked a range of nonrenewable and renewable energy sources based on the aforementioned criteria without considering cost as a determining factor and concluded that wind, concentrated solar power (CSP), geothermal, tidal, solar, wave, and hydropower are the best options for electricity generation, while biofuels are the worst. Roth et al. (2009) studied the sustainability of current and future electricity supply technologies from the environmental, social and economic points of view and reported hydropower, geothermal, and biogas technologies as the best energy alternatives. Chatzimouratidis and Pilavachi (2009a) evaluated power plants based on technological, sustainability, and economic criteria using AHP and suggested renewable energy and fossil fuel power plants as the best and the worst options among ten different alternatives. Oberschmidt et al. (2010) evaluated different energy alternatives for electricity and heat supply using a Modified PROMETHEE method and concluded that renewable sources are more promising. Kahraman et al. (2009), Kahraman and Kaya (2010), and Kaya and Kahraman (2010) ranked different renewable energies that are best suited for future investment in Turkey, taking into account their technical, economic, environmental, political, and social aspects. Their results suggested wind power as the best alternative. San Cristóbal (2011) investigated various renewable energy sources in Spain based on different criteria, such as power, investment ratio, implementation period, operating hours, useful life, operation and maintenance costs, and tons of CO2 avoided. He found biomass, wind, and solar energies as the best alternatives.

The extensive applications of systems methods in energy planning reflect the fact that the field has correctly realized the complexity of the problem and identified the proper framework for developing long-term energy plans and assessing energy sustainability. However, significant differences between the study results indicate the inconsistency in the assumptions and methods applied in the previous studies due to three major limitations:

a) Different notions of optimality: Given the difference in the notion of optimality, various multi-criteria assessment methods result in different ‘optimal’ outcomes and rankings (Madani et al., 2014b) of energy alternatives. This makes the study results highly sensitive to the choice of multi-criteria assessment method. Therefore, there is a need to develop a more robust assessment procedure, which minimizes the results’ sensitivity to the analyst’s choice of multi-criteria assessment method.

b) Uncertainty in performance values: The performance of energy production options under different assessment criteria (carbon footprint, water footprint, cost, etc.) depends on a variety of factors, including regional conditions and technologic maturity. So, the estimation of the performance values at a large scale (e.g. global) becomes very challenging and controversial. While some studies have suggested different methods to consider uncertainty in energy planning (Ryll et al., 2001; Gamou et al., 2002; Borges and Antunes, 2003; Mavrotas et al., 2008; Chen et al., 2007; Cai et al., 2011b; Li et al., 2011b; Wang et al., 2010; Zang et al., 2012; Zhou et al., 2012) most of the literature overlooks the high level of uncertainty in performance values at different geographical scales. Usually, energy planning studies use deterministic performance values and/or use different methods which provide deterministic outputs despite uncertain input information, hiding the risks associated with the study results. Thus, there is a need to develop a method which considers the uncertainties involved and inform the decision makers about the uncertainties’ impacts on the assessment of the results and their robustness.

c) Lack of a reliable aggregating index: In fact, most studies have investigated only one aspect of sustainability in attempt to suggest a sustainability index, which often leads to ineffective sustainability measures (Singh et al., 2009, 2012). As discussed, different system level life-cycle indicators (water footprint, carbon footprint, etc.) and other sustainability indicators provide valuable information, but their focus is normally limited on particular aspect(s) of sustainability, making them ineffective for sustainability evaluation (Singh et al., 2009, 2012; Hjorth and Madani, 2014). Indeed, the literature lacks a reliable aggregating indicator that can provide useful quantitative information to policy makers. Therefore, there is a need to develop a robust aggregating indicator at the appropriate level (SoS level) that conveys useful quantitative information to decision makers with respect to performance uncertainty and performances under the lower level indicators.

This paper develops a new energy sustainability assessment framework that addresses these limitations. To counterbalance the bias toward definition of optimality by a single multi-criteria analysis method and increase the robustness of analysis, this study employs multiple multi-criteria decision making (MCDM) methods. Among the many methods available for multi-criteria analysis, five MCDM methods (Table 2) are applied here to investigate the footprint of different energy sources. The selected methods are mostly suitable for social planner problems (Linkov et al., 2004, 2005; Madani et al., 2014b), in which a central decision maker is interested in identifying the system-wide optimal solution. To account for the performance uncertainties (Table 1), multi-criteria assessment is combined with a Monte-Carlo selection. Monte-Carlo multi-criteria assessment under uncertainty (Madani and Lund, 2011; Madani et al., 2014c) maps the stochastic decision making
problem into numerous (100,000 in this study) deterministic problems by generating random numbers from the uncertainty intervals for the alternative energy sources. Each deterministic decision making problem is then solved and the energy sources are ranked using each MCDM method with respect to the four lower level criteria (carbon footprint, water footprint, land footprint, and cost). The winning probability of each alternative at each rank (Madani et al., 2014c) under each MCDM method is then calculated based on the results of 100,000 deterministic MCDM analyses. The winner alternative at each rank is selected to establish the final ranking under each MCDM method. Further details about this procedure can be found in Mokhtari et al. (2012) and Mokhtari (2013). For detailed mathematical descriptions of the five MCDM methods used in this study (Table 2), readers are referred to Madani et al. (2014b).

Given that the overall rankings of the alternatives under each MCDM method are not necessarily identical (due to their different notions of optimality) there is a need for an aggregation method for establishing the overall ranking, which is more robust. “Relative Aggregate Footprint (RAF)” is proposed here as an SoS index to evaluate the overall desirability of energy alternatives with respect to different evaluation criteria and performance uncertainties. The value of this index can be identified for each alternative using the following equation:

\[
RAF_i = 100 \left[ 1 - \left( \frac{C.N - B_i}{N(C - 1)} \right) \right]
\]

where \( C \): number of alternatives; \( N \): number of MCDM methods; \( B_i \): Borda score of alternative \( i \) (Borda score (Borda, 1781) is the sum of the scores (ranks) given to each energy alternative by different MCDM methods); and \( RAF_i \): relative aggregate footprint of alternative \( i \).

\( RAF_i \) varies from 0 to 100, where 100 is given to the absolute worst alternative with the maximum possible RAF and 0 is given to the absolute best alternative with the minimum possible RAF. Based on Equation 1, the absolute best (strictly dominant) alternative is the one that receives a RAF score of 0 by being ranked as the best under all MCDM methods (all definitions of optimality). On contrary, the absolute worst (strictly dominated) alternative is the alternative with a RAF score of 100 as a result of being ranked as the worst alternative under all MCDM methods. Relative resource-use efficiency of an energy alternative (RRUE) can be defined as 100–RAF, as an alternative indicator, reflecting the aggregate efficiency of resource (water, land, climate emission capacity, economic reserve) use for energy production. In that case, RRUE of 100 and 0, respectively reflect the highest and lowest possible aggregate efficiency of resource use.

This study uses four evaluation criteria (levelized cost, carbon footprint, water footprint and land footprint), fifteen alternatives (Table 1) and five MCDM methods (Table 2) to calculate the RAF of different energy sources. Nonetheless, the proposed SoS framework and RAF formulation (Eq. (1)) are general and can be applied to evaluate the aggregate desirability of any number of alternatives, under any number of (at least two) criteria, using any number of decision analysis methods.

3. Results and discussion

3.1. Relative aggregate footprint scores

Table 3 shows the overall ranking of energy alternatives based on different MCDM methods. These rankings are based on the winning probabilities calculated using the Monte-Carlo MCDM method (Mokhtari et al., 2012; Mokhtari, 2013) with 100,000 rounds of selection. In this global scale proof-of-concept study, the four lower system level criteria have been assumed to be equally important to the central energy planner. This assumption is not true in case of regional restriction in the availability of one or more of the main resources (e.g. water and land). So, the weights can be adjusted accordingly considering the decision makers’ preferences at the local level.

As expected, the rankings under different MCDM methods are not identical. A more robust ranking can be established by calculating the RAF of the energy alternatives based on Eq. (1), using the information provided in Table 3. Fig. 2 shows the RAFs of different energy alternatives. In this figure, energy sources have been categorized into three groups (highly efficient, efficient, inefficient) based on the magnitude of differences between their RAF scores. The first group does not include any fossil energy sources, which reflects the

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Dominance</th>
<th>Maximin</th>
<th>SAW</th>
<th>Lexicographic</th>
<th>TOPSIS</th>
<th>Average Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol from corn</td>
<td>12</td>
<td>9</td>
<td>15</td>
<td>13</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Ethanol from sugar cane</td>
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<tr>
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</tr>
<tr>
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<td>4</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
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Fig. 2. Relative aggregate footprint (RAF) of different energy sources (0–100).

general desirability of renewable energy sources. However, different biofuels belong to the inefficient (with high RAF) energy group that also includes coal and oil. This finding proves that renewable might not be as desirable as perceived when a SoS perspective is adopted. On the other hand, some energy sources such as nuclear and natural gas can be competitive with most renewable energies based on their overall RAF. The fact that no energy resource has received a RAF of 0 or 100 shows that there is no strictly dominant (best) and strictly dominated (worst) energy supply option, due to the performance value uncertainties and different notions of optimality.

While geothermal is not the best energy option in terms of energy production costs or emissions, it has the lowest RAF (6) based on the four resource use efficiency criteria considered in this analysis. This clearly shows how a holistic view of energy production effects on different resources based on a SoS approach can change desirability of an energy source, which might not be highly desirable based on one or two specific criteria. Nevertheless, forecasts by the Energy Information Administration (EIA, 2011b) indicate only a 0.06% increase in share of geothermal in the global energy supply portfolio in the period of 2011–2035. It should be noted that the desirability of energy sources in general should be distinguished from their technical feasibility. While the former specifies the magnitude of aggregate footprint of energy production from the resource use perspective, the latter is associated with the viability of energy production in a given region based on resource and technologic availability conditions. For instance, while expansion of geothermal energy is encouraged based on the results here, factors such as the availability and deepness of geothermal vents as well as unavailability of the required technologies can limit the adoption of geothermal energy in certain regions.

Similar to geothermal energy, wind (onshore and offshore) energy is one of the most efficient options (RAFT = 12) based on a SoS perspective. However, the share of this energy is supposed to increase by only 1.5% in the next two decades (EIA, 2011b). The small increase in the share of wind from the world’s total energy production could be related to the geographic limitations as well as the cost of energy production from wind in countries in which this energy source is still immature. In many advanced economies, however, the energy production from wind is increasing rapidly. For instance, wind energy has had a growth of more than 2000% in the U.S. during the 1995–2009 period (EIA, 2012b).

Solar thermal is the next resource-use efficient energy source (RAFT = 17). Compared to solar photovoltaic (PV) (RAFT = 54), solar thermal is more efficient due to the lower estimates of carbon, land, and economic footprints in the literature. However, solar PV is the solar energy option that is gaining more popularity, mainly due to its ease of accessibility and use. The overall resource-use efficiency of solar PV could be increased by improving its production technology and recycling PV materials after their useful life (Pthenakis, 2000). This would yield a lower emission, cost, and land use per unit of energy production and makes this energy alternative more resource-use efficient.

According to Fig. 2, nuclear energy with the RAF value of 24 is the most attractive nonrenewable energy source. Although safety issues, international laws and regulations, nuclear waste, and the lack of required technologies and materials could be the main barriers to further development of this energy, from a holistic resource use perspective, nuclear energy is more efficient compared to some renewables such as hydropower, solar PV, ethanol, and biofuels.

Wave and tidal energies are renewable energy sources with a relatively low RAF (30). Despite their power generation inefficiency that yields fairly high carbon footprint and cost, their low water use and land use make them more efficient compared to more popular renewable power sources such as hydropower, solar photovoltaic and biofuels. However, technological barriers, production costs, and large-scale implementation limitations, are the main reasons for the small share of wind and tidal energies from the world’s total energy mix.

Hydropower has been the most commonly used renewable energy source for a long time. However, this energy option has a RAF value of 53 because of its considerable water footprint (due to evaporative losses from hydropower reservoirs and their water quality effects) and land footprints (due to the area of land required for storing water and placing different hydropower facilities). It is noteworthy that this study uses the average performance values of hydropower for evaluating its overall resource efficiencies. But, water and land footprints are not expected to be so significant in case of small and run-of-river hydropower. Therefore, the small and run-of-river hydropower systems have higher resource use efficiencies (lower RAFs) under the considered sustainability criteria in this study, making them more desirable in sustainable energy planning.

Natural gas (RAFT = 60) is the most resource-use efficient fossil fuel and has the highest RAF among the widely used fossil energies. Compared to coal (RAFT = 73) and oil (RAFT = 83), natural gas has lower carbon and water footprints. RAF of natural gas is very close to some renewable energy sources such as hydropower and solar PV. Also, it is more resource-use efficient than biofuels. This is despite the fact that due to its relatively high carbon footprint and cost, natural
gas is not a competitive energy option if tackling climate change or low-cost energy production are the only concerns. Natural gas can become a more competitive energy option with renewables if its cost and carbon emissions are lowered.

Despite their relatively low costs, energy from woodchip and miscanthus (with RAFs of 76 and 84, respectively) and ethanol from sugarcane and corn (with RAFs of 70 and 84) are among the least efficient alternatives based on considered criteria. This is mainly because of the considerable land and water footprints of these energy sources. While the current energy policies in many parts of the world promote biofuel and ethanol as reliable energy alternatives to fossil fuels (European Union, 2011; Pimentel et al., 2009), our results suggest that a SoS perspective that carefully considers the possible secondary impacts of energy production on land and water resources, makes these energies highly inefficient.

Overall, the obtained results suggest that based on the SoS perspective, renewable energy sources are not necessarily ‘green’ as they are generally perceived. It must be emphasized that this counter-intuitive finding does not mean that ecosystem damages can be avoided by continued reliance upon fossil fuels and by excluding renewables from the energy supply mix. Instead, we need to invest in technological improvements that make renewable energy sources more efficient, mostly in terms of land and water use efficiency. Some renewables such as solar PV, hydropower, biofuels, and ethanol need further investigations if we do not like to mitigate global warming by exhausting valuable natural resources. A SoS approach helps us appreciate the trade-offs involved between the effects of energy production on different components of the complex human-natural SoS and develop energy management plans that effectively reduce GHG emissions at a reasonable cost with minimal secondary impacts.

### 3.2. Robustness and sensitivity analysis

The Monte-Carlo MCDM method used here orders energy alternatives under each MCDM method based on their winning probabilities at each rank. Once the option with the highest winning probability is determined as the best alternative (rank 1) based on a given method, this option is removed from the alternatives set and the winning probabilities are calculated for the remaining options by repeating the same process (Madani et al., 2014c). Based on this method, while the input performance values are uncertain, the resulting RAF scores are deterministic. This might hide the uncertainty associated with the RAF calculations from the decision makers. To address this limitation, and for better understanding of the risks associated with selection of different energy alternatives, the mean and standard deviation of the RAF score of each energy alternative can be evaluated. To calculate the mean and standard deviation of RAF scores, the RAF score is calculated for all energy sources in each round of the Monte-Carlo selection. Eventually, a RAF score distribution is developed for each alternative.

Table 4 provides the mean and standard deviation of the energy RAFs, calculated based on 100,000 rounds of Monte-Carlo sampling. Mean RAFs are within 5% of the RAFs calculated in the previous step by applying Eq. (1) at the end of the Monte-Carlo selection process using the overall ranks, as opposed to applying Eq. (1) at the end of each round of Monte-Carlo selection using the ranks specific to that round of selection only. This shows the reasonable reliability of the calculated RAF values in the previous step, which required significantly less computational effort.

![Fig. 3. Comparison of energy sources’ RAF sensitivity to the considered efficiency criteria (C, carbon footprint; W, water footprint; L, land footprint; and $, cost). The dashed horizontal line shows the RAF = 50 level to facilitate comparison. The CWL$ line shows the RAF scores when all four criteria are considered (as shown previously in Fig. 2).](image-url)
Relatively low standard deviations in Table 4 imply a high degree of robustness in the calculated RAFs. Among all sources, hydropower, nuclear, biomass from miscanthus, as well as wave and tidal energies have the least robust RAFs under the existing performance values (Table 1), while solar thermal, onshore wind, and ethanol have the most robust efficiency scores.

In addition to the degree of robustness information, decision makers can benefit from learning about the sensitivity of RAF scores to exclusion/inclusion of different criteria from the analysis. Sensitivity analysis also helps with understanding the major drawbacks of different energy sources that are in need of being addressed in order to improve their efficiency scores significantly. For example, learning the fact that the high water footprint of biofuels is one of the main reasons for their inefficiency would encourage investment and research in the technological improvements that can help with minimizing the biofuels’ water footprint. Moreover, given that the importance of different sustainability criteria (carbon footprint, water footprint, etc.) varies regionally depending on the availability of local resources, the sensitivity analysis information can help selecting the best energy source.

Fig. 4. Individual energy RAF resource sensitivity charts, reflecting RAF sensitivity to the considered efficiency criteria (C, carbon footprint; W, water footprint; L, land footprint; and $, cost). The RAF value is 0 at the center of the radar chart and 100 at the edge of the chart.
supply sources according to the local limitations. For example, hydropower could be a desirable renewable resource where water and land availability is not a limitation (e.g., Canada).

To examine the sensitivity of the calculated RAFs to the four considered criteria (carbon footprint (C), water footprint (W), land footprint (L), and cost ($)), the Monte-Carlo MCDM analysis was repeated using all subsets of these equally weighted criteria. Fig. 3 shows the degree of RAF sensitivity to varying resource availability conditions, represented by inclusion/exclusion of different resource use efficiency criteria. For example, it can be assumed that where water is abundant, water footprint is not an issue of concern and RAF can be determined using CLS (by excluding W).

The sensitivity degree of each energy’s RAF to resource availability conditions is determined based on the difference between the minimum and maximum RAF of that energy in Fig. 3. The higher the difference, the more resource-sensitive the energy. Generally, the energy sources’ RAF is highly sensitive to the set of evaluation criteria. However, the degree of sensitivity varies between different energy options, irrespective of their RAF values. For example, while geothermal shows a lower degree of sensitivity, ethanol has a high degree of sensitivity. This means that desirability of geothermal is less dependent than the desirability of ethanol on the local resource availability conditions. Also, biomass from miscanthus shows a low sensitivity to different analysis criteria despite its large RAF value, indicating that there is no meaningful relationship between the RAF value and its sensitivity.

Given the complexity of Fig. 3, individual RAF sensitivity charts have been developed for each energy source (Fig. 4) to show how each energy alternative’s RAF varies depending on the subset of criteria considered according to the resource availability conditions. In these charts, a smaller radar coverage area (shaded in red) shows a higher desirability, or a generally lower RAF under different resource availability conditions. Large radar coverage, however, shows a low desirability or a high RAF. Generally, a smoother RAF fluctuation pattern (more circular RAF) reflects lower sensitivity to the resource availability conditions (analysis criteria). On the other hand, a fluctuating RAF pattern shows high sensitivity to resource availability conditions. For example, biomass from miscanthus and ethanol from sugarcane, respectively, show low and high RAF sensitivities to varying resource availability conditions.

Based on Figs. 3 and 4, geothermal energy shows the lowest RAF sensitivity (difference between the maximum and minimum RAF scores obtained) to resource availability conditions. A low RAF coupled with a low RAF sensitivity makes geothermal energy both efficient and reliable, if the required geographic and geological conditions for implementing this energy option are available. Although onshore and offshore wind energy sources have high resource-use efficiencies, their RAFs are fairly sensitive to the resource availability conditions, making these options undesirable where land availability is an important concern for the decision makers. Solar thermal shows a lower RAF sensitivity than solar PV to different resource availability constraints. The RAF of solar thermal, however, is sensitive to the cost criterion, meaning that solar thermal is not a competitive energy option in poor economies. Nuclear energy shows a lower sensitivity to different resource availability conditions when compared to some renewable sources such as wind, solar PV, and wave/tidal. With the lowest land use among all energy sources as well as low costs, the nuclear energy could become much more resource-use efficient if its water footprint is improved considerably. Nevertheless, with the Fukushima experience, future studies need to carefully reconsider the land footprint estimations for nuclear energy as a significantly larger land use might be required (e.g., for expansion of the protected/undeveloped zone around nuclear plants) to increase the safety of nuclear facilities. Similar to wind energy, wave and tidal energies show a high RAF sensitivity and become less desirable as energy production cost becomes more important to the decision makers.

Hydropower has one of the lowest RAF sensitivity values, suggesting that its RAF score does not change significantly under various resource availability conditions. Land and water footprint become less significant with smaller-scale hydropower facilities and when hydropower production is an ancillary benefit of reservoir operations. The latter is valid in case of multi-objective reservoirs where the high footprint of the reservoirs must not be only attributed to hydropower production.

Natural gas is not an appropriate energy option when GHG emissions are the main concern. However, its overall RAF score and fairly low RAF sensitivity could make this energy an appropriate option in some parts of the world, depending on the local resource availability conditions. As the major source of energy in industrial and transportation sectors in many parts of the world, oil has a low RAF sensitivity to resource availability. Given its low RAF, this energy source is not generally desirable, irrespective of the resource availability conditions. The desirability of biofuels is highly dependent on resource availability conditions, except for biomass from miscanthus with its fairly low RAF sensitivity range. Improving the water-use efficiency of biofuels (lowering their water footprint) is the main key to increase their desirability.

4. Conclusions

Current energy mixes are extensively dependent on the continued extensive use of natural and economic resources, while producing considerable amounts of GHG emissions that result in further climate warming. To achieve a sustainable energy mix that addresses the increasing energy demand and energy security with minimal impacts on our scarce resources, we need to consider the complex interactions of the energy system with other systems (water, land, climate, economy) and acknowledge the uncertainties involved in multi-attribute decision-making. Hence, a higher-level system of systems (SoS) perspective that accounts for the trade-offs between lower-level system components is desired. This paper proposed a SoS framework to evaluate the overall resource-use efficiency of energy sources with respect to such trade-offs and the associated uncertainties. For this purpose, a stochastic multi-criteria analysis framework was used to estimate the relative aggregate footprint (RAF) scores of energy sources under different sustainability criteria, e.g., carbon footprint, water footprint, land footprint, and cost of energy production. The developed framework employs a range of MCDM methods to eliminate the possible biases resulting from unique optimality definitions of the different MCDM methods and provides a robust and relative comparison of the desirability of energy sources under different optimality notions.

Based on the four equally weighted sustainability criteria considered in this study, geothermal and biomass from miscanthus are the best and worst energy options, respectively. This, however, does not guarantee that the resource-use efficient energy sources (geothermal, wind, solar thermal, nuclear, and wave and tidal energies) remain desirable with local resource limitation conditions. Hence, a sensitivity analysis was performed to measure the variability of energy RAFs under different resource availability conditions. The sensitivity analysis results indicate that geothermal and ethanol from sugarcane show the lowest and highest sensitivity to resource availability conditions. The impacts of existing performance uncertainties on the energy RAFs were also measured to determine the robustness of the energy RAFs. The robustness analysis results indicate that hydropower and solar thermal have the most and least robust energy RAFs under the existing performance uncertainties.
Our results clearly indicate that from a SoS perspective, some of the renewable energy sources such as hydropower and solar PV are not as ‘green’ as perceived based on the current state of the energy production methods/technologies. The RAFs of some popular renewable energy sources such as biofuel and ethanol are even worse than some fossil fuels such as natural gas, mainly due to their high water and land footprints, which have been largely overlooked by those policy makers, determined to solve global warming problems simply by replacing fossil fuels with renewables. Improving the desirability of renewables in terms of GHG emissions, water consumption, land use, and production costs can prevent major damages to different components of the coupled human-natural SoS.

This study intended to develop a general SoS framework for energy sustainability evaluation. However, this proof-of-concept study, has some limitations that could be addressed in future studies. First, the sustainability criteria in this study were weighted equally and did not clearly reflect the regional desirability of energy sources. Future studies can carefully consider the regional resource availability conditions and assign different weights to the sustainability criteria to determine regionally specific energy RAFs. Second, the feasibility of energy alternatives in different regions should be taken into account, as not all energy sources are accessible in all regions due to different physical, technological, legal and institutional barriers. Third, other sustainability criteria can be added to the analysis to form a more realistic evaluation of the regional desirability of different energy sources based on the regional concerns and social, political, and safety attributes. Finally, while technology improvements could potentially lead to the improvement of performance values, fixed performance values were used in the analysis. Such performance improvements could be addressed in future studies to determine how the energy RAFs can change over time.

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