Importance of Life Cycle Assessment of Renewable Energy Sources

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Abstract The increasing demand for sustainable renewable energy sources to reduce the pollution and dependency on conventional energy resources creates a path to assess the various energy sources for their sustainability. One renewable energy source might be very attractive for heat production and not so attractive for electricity and transport purposes. The commercial-scale production of these energy sources requires careful consideration of several issues that can be broadly categorized as raw material production, technology, by-products, etc. The life cycle assessment (LCA) is a tool that can be used effectively in evaluating various renewable energy sources for their sustainability and can help policy makers choose the best energy source for specific purpose. Choice of allocation method is very important in assessing the sustainability of energy source as different allocation methods respond in present differently. The present chapter is an effort to highlight the importance of LCA of renewable energy sources.

1 Introduction

Progressive depletion of conventional fossil fuels with increasing energy consumption and greenhouse gas (GHG) emissions has led to a move toward renewable and sustainable energy sources (Singh et al. 2011, 2012; Nigam and

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Singh 2011). The production of sustainable energy based on renewable sources is a challenging task for replacing the fossil-based fuels to get cleaner environment and also to reduce the dependency on other countries and uncertainty of fuel price (Singh and Olsen 2012, 2011; Pant et al. 2012). A worrying statistic is that the global production of oil and gas is approaching its maximum and the world is now finding one new barrel of oil for every four it consumes (Aleklett and Campbell 2003). All these serious concerns related to energy security, environment, and sustainability have led to a move toward alternative, renewable, sustainable, efficient, and cost-effective energy sources with lesser emissions (Prasad et al. 2007a, b; Singh and Olsen 2012).

The life cycle assessment (LCA) of renewable energy sources is the key to observe their sustainability. There is a need to conduct LCA of renewable energy production system on the basis of their local conditions, as one energy source cannot be sustainable for all geographical locations, due to variations in resources availability, climate, environmental, economical and social conditions, policies, etc. Therefore, LCA can be used as a tool to assess the sustainability of various energy sources for different locations. LCA techniques allow detailed analysis of material and energy fluxes on regional and global scales. This includes indirect inputs to the production process and associated wastes and emissions, and the downstream fate of products in the future (Singh et al. 2011). LCA studies vary in their definition of the various criteria, such as, scope and goal, system boundaries, reference system, allocation method. LCA studies of renewable energy sources calculate the environmental impact and can relate the results against sustainability criteria. The present chapter is an effort to highlight the importance of LCA of renewable energy sources to get a more holistic perspective of their environmental sustainability.

2 Renewable Energy Sources

The most common renewable energy sources are presented in the Fig. 1. Each renewable energy source is performing differently; one could be best option for one location/purpose/season and could not perform with that efficiency at another location/purpose/season. The solar energy sources are best in remote or under developed areas having bright sunshine (Jayakumar 2009). Windmills are best suited near sea shore, as there winds are enough strong to get decent production of energy. Similarly, tidal, hydroelectric, geothermal, and ocean thermal energies have their importance. Among the renewable energy sources, biofuels are the most popular renewable energy source because of the availability of raw material (biomass), everywhere and round the year and also due to its suitability in transport vehicles and industries. The detailed description of different biofuels is published by Nigam and Singh (2011).

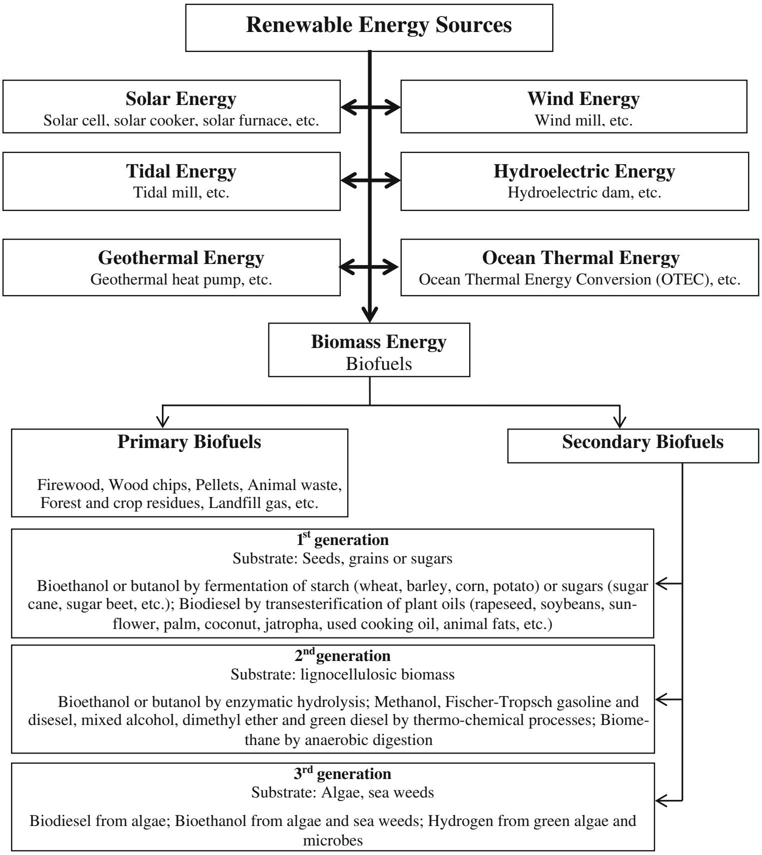

Fig. 1 The most important renewable energy sources

3 Life Cycle Assessment

ISO 14040 defined LCA as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 2006). Thus, LCA is a tool to assess the environmental impacts and resources used throughout a product's life cycle and consider all attributes or aspects of natural environment, human health, and resources (Korres et al. 2010) and can be defined as a method for analyzing and assessing environmental impacts of a material, product, or service along its entire life cycle (ISO 2005). LCA analyzes the environmental burden of products at all stages in their life cycle (from the cradle to the grave) from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, by recycling, or by final disposal (Guinée 2004).

Table 1 Overview of LCA methodological steps (Adapted from Guinée 2004)

Phase	Steps	Main result
Goal and scope definition	Procedure	Functional unit, alternatives compared
	Goal definition	
	Scope definition	
	Function, functional unit, alternative and reference flows	
Inventory analysis	Procedure	Inventory table, other indication (e.g., missing flows)
	Economy—environmental system boundary	
	Flow diagram	
	Format and data categories	
	Data quality	
	Data collection and relating data to unit processes	
	Data validation	
	Cutoff and data estimation	
	Multifunctionality and allocation	
	Calculation method	
Impact assessment	Procedures	Environmental profile
	Selection of impact categories	Normalized environmental profile
	Selection of characterization methods: category indicators, characterization models	Weighting profile
	Classification	
	Characterization	
	Normalization	
	Grouping	
	Weighting	
Interpretation	Procedure	Well-balanced conclusion and recommendations
	Consistency check	
	Completeness check	
	Contribution analysis	
	Perturbation analysis	
	Sensitivity and uncertainty analysis	
	Conclusions and recommendations	

Various steps involved in the LCA methodology are listed in Table 1. The complete life cycle of the renewable energy sources includes each and every step from raw material production and extraction, processing, transportation, manufacturing, storage, distribution, and utilization. Each of these can have an impact (harmful or beneficial) of different environmental, economical, and social dimensions. It is therefore of crucial importance to assess the complete fuel chains from different perspectives in order to achieve sustainable biofuels (Markevičius et al. 2010).

The environmental burden covers all types of impacts on the environment, including extraction of different types of resources, emission of hazardous substances, and different types of land use. Reinhard and Zah (2011) distinguished the two main approaches of LCA, i.e., the attributional and the consequential approach: both approaches differ with respect to system delimitation and the use of average versus marginal data. Attributional LCA describes the environmentally relevant physical flows to and from a life cycle and its subsystems, while consequential LCA describes how environmentally relevant flows will change in response to possible decisions. Marginal data are represented by the product, resource, supplier, or technology, which are the most sensitive to changes in demand, and economic value criteria are used to identify the marginal products (Ekvall and Weidema 2004).

Attributional LCA is limited to a single full life cycle from cradle to grave, and consequential LCA is not limited to one life cycle, but uses system enlargement to include the life cycles of the products affected by a change in the multifunctional processes will often be handled through allocation, physical flows in the central life cycle. In attributional LCA multifunctional processes will often be handled through allocation, while in consequential LCA, allocation will generally be avoided through the system expansion. Additionally, marginal data are used, whereas average data are applied in attributional LCA (Ekvall and Weidema 2004; Reinhard and Zah 2011).

Various scientists have employed LCA on renewable energy production systems (Reinhard and Zah 2011; Biswas et al. 2011; Ribeiro and Silva 2010; Gabrielle and Gagnaire 2008; Gnansounou et al. 2009; Kiwjaroun et al. 2009; Martínez et al. 2009; Suri et al. 2007; Laleman et al. 2011; Zah et al. 2007), and some useful results considering the factors (e.g., biomass, technologies, use, system boundary, allocation, reference system) affecting the outcome of the analysis have been obtained (Singh et al. 2010).

4 Importance of Life Cycle Assessment

The purpose of LCA is to compile and evaluate the environmental consequences of different options for fulfilling a certain function (Guinée 2004), and it is a universally accepted approach of determining the environmental consequences of a particular product over its entire production cycle (Pant et al. 2011). The LCA methodology can be useful to acquire a comprehensive knowledge of the environmental impacts generated by industrial products during their whole life cycle (de Eicker et al. 2010). LCA can play a useful role in public and private environmental management in relation to products as this may involve both an environmental comparison between existing products and the development of new products (Guinée 2004). LCA has been the method of choice in recent years for various kinds of new technologies for bioenergy and carbon sequestration.

The "holistic" nature of LCA depicts both its major strength and, at the same time, its limitation. The broad scope of analyzing the complete life cycle of a product can only be achieved at the expense of simplifying other aspects (Guinée 2004). LCA of renewable energy production system requires a careful design regarding the goal and scope definition, choice of functional unit, reference system, system boundaries and appropriate inventory establishment and allocation of emissions in products and by-products (Singh and Olsen 2012). Larson (2006) describes four input parameters to cause the greatest variation and uncertainties in LCA results of energy production, namely climate-active plant species (species with ability or otherwise to adapt to climate change); assumptions about N_2O emissions; the allocation method for co-product credits; and soil carbon dynamics.

In general, LCA is in fact developed for impacts with an input–output character, and extractions from the environment and emissions to the environment can both be well linked to a functional unit (Udo de Haes and Heijungs 2007). LCA regards all processes as linear, both in the economy and in the environment. The LCA model focuses on physical characteristics of the industrial activities and other economic processes; the attributional LCA does not include market mechanisms or secondary effects on technological development (Guinée 2004).

The results of LCA study are as much science based as possible and aim to enlighten stakeholders in a production–consumption chain, thus contributing to rational decision-making. LCA study can also be of use inside a company; by implementing an LCA study on a product, the processes of the product system can be identified, which largely appear to contribute to its total environmental burden. This may help to direct environmental management of the company, for instance to support its investment decisions or to influence its supply management (Udo de Haes and Heijungs 2007). The main applications of LCA are analyses of the origins of problems related to a particular product; comparing improvement variants of a given product; designing new products; choosing between a number of comparable products. Similar applications can be distinguished at a strategic level, dealing with government policies and business strategies for renewable and sustainable energy source. The way an LCA project is implemented depends on the intended use of the LCA results (Guinée 2004). This reasoning can be predominantly true for decisions in the energy sector. In year 2010, EPA applied the consequential LCA approach in its regulation for US renewable fuel standards under the 2007 US Energy Independence and Security Act (RFS2, as opposed to renewable fuel standards under the 2005 U.S. Energy Policy Act, RFS1) (EPA 2010; Wang et al. 2011).

5 LCA and Sustainability of Renewable Energy Sources

The general principles of sustainable biofuel production are relatively easy to define (as shown in Fig. 2). However, it is quite challenging to derive a sound framework that is able to characterize environmental, economical, and social impacts in an adequate way. World Commission on Environment and Development defined the term “sustainability” as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (UNCED 1992). The methodologies to address LCA and sustainability are advancing although the availability of practical data remains an issue (Black et al. 2011). Sustainable development can be defined as the fulfillment

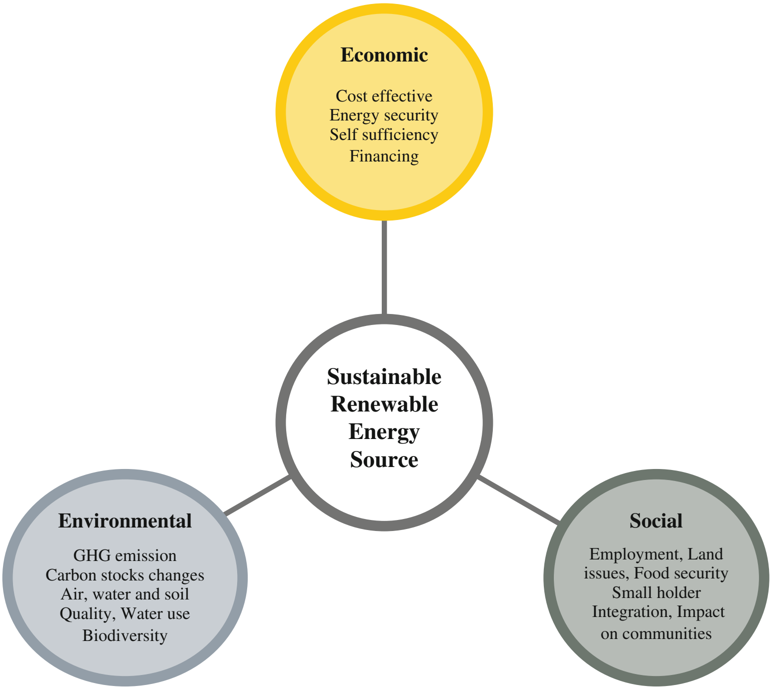

Fig. 2 Economic, social, and environmental aspects of sustainable renewable energy sources (Adapted from IEA 2011; Singh and Olsen 2012)

through the optimal use of any available source within a production system. Energy conversion, utilization, and access underlie many of the great challenges associated with sustainability, environmental quality, security, and poverty (Korres et al. 2010, 2011). Sustainability assessment of products or technologies is normally seen as encompassing impacts in three dimensions, i.e., social, environmental, and economic (Elkington 1998). These three dimensions form the backbone of sustainability standards. To replace the fossil fuels with biofuels, there is a need to maximize the environmental and social value of biofuels that is also important for the future of biofuels industry and market potential depends on being cost competitive with fossil fuels (Fig. 2). The environmental dimension comprises amongst others the GHG emissions, global ecological performance, conservation of energy resources, rational life cycle water use, effect on soil quality, conservation of biodiversity, use of chemicals, and the practice of slash and burn and the socioeconomic dimensions includes competition with food and feed, contribution to local well being, impact on communities and the quality of working conditions. These three interrelated goals must stay in balance for biofuels to remain sustainable.

Environmental impacts occur in all stages of the energy production system: the transformation of the land needed, production and application of chemicals and other input, cultivation of energy crops, production of the biofuel, transportation to the gauging station, and use in the vehicle. Pollutants are generated in many different steps of the production chain. The sustainability of renewable energy production depends on the net energy gain fixed in the output that depends on the production process parameters, such as the amount of energy-intensive inputs and the energy input for harvest, transport and running the processing facilities (Haye and Hardtke 2009), emissions and their production cost. The most used indicators to measure the energy sustainability include life cycle energy balance, quantity of fossil energy substituted per hectare, co-product energy allocation, life cycle carbon balance, and changes in soil utilization (Silva Lora et al. 2011). Gnansounou et al. (2009) stated that monitoring reduction in GHG emissions and estimations of substitution efficiency with respect to fossil fuels is subject to significant uncertainty and inaccuracy associated with the LCA approach.

The schematic illustration of the technical biomass potential and constraints to the sustainable biomass potentials is presented in the Fig. 3. The technical potential of biomass is much lower than the theoretical potential due to cost involved in transport to collect them at production plant. The technical potential also has several social, economical, and environmental constraints, resulting only in a part of the technical potential that could be suitable for sustainable renewable energy production. Gnansounou (2011) suggested that due to the multidimensional impact of renewable energy sources, the sustainability impact assessment of

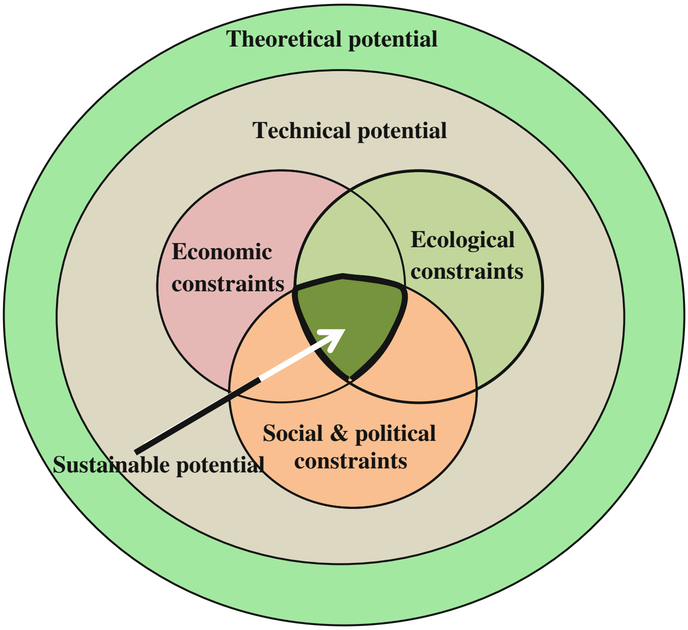

Fig. 3 Schematic illustration of the technical potential and constraints to the sustainable biomass potentials (Adapted from Steubing et al. 2010)

policies is as relevant as the sustainability assessment of production pathways and regulatory impact assessment.

Sustainability evaluation of biofuels is a multicriterial problem; Silva Lora et al. (2011) suggests the following main indicators for a sustainable energy production:

- To be carbon neutral.
- Not to affect the quality, quantity, and rational use of available natural resources.
- Not to affect the biodiversity.
- Not to have undesirable social consequences.
- To contribute to the societal economic development and equity.

The major factors that will determine the impacts of renewable energy production system include their contribution to land use change, the feedstock/input used, technology adopted, scale of production, use of by-products (if any), wholesale trade and retail of energy product and by-product, and emissions after end use of produced energy. Yan and Lin (2009) revealed that the interactions among various sustainability issues make the assessment of biofuel development difficult and complicated. The complexity during the whole renewable energy production chain generates significantly different results due to the differences in input data, methodologies applied, and local geographical conditions.

In order to ensure net societal benefits of biofuels production, governments, researchers, and companies will need to work together to carry out comprehensive assessments, map suitable and unsuitable areas, and define and apply standards relevant to the different circumstances of each country (Phalan 2009). The length and complexity of the supply chains make the sustainability issue very challenging. The main aim is to improve the performance of the strategies by enhancing positive effects, mitigating negative ones, and avoiding the transfer of negative impacts to future generations (Gnansounou 2011). The science of LCA is being stretched to its limits as policy makers consider direct and indirect effects of biofuels on global land and water resources, global ecosystems, air quality, public health, and social justice (Sheehan 2009). The sustainable renewable energy production is directed by environmental impacts (direct and indirect), economic viability including societal and political acceptance.

6 Conclusions

The increasing demand for renewable energy challenges societies to find out sustainable and renewable energy source. LCA is a tool which can be used effectively in assessing the sustainability of renewable energy sources. The collection of actual data for such study is a quite challenging task, as these data sets have very high variations with the temporal and spatial variation. The sustainability basically depends on three pillars of social, economical, and environmental performance of the renewable energy source. The social, economical, and environmental constraints reduce the potential of sustainable renewable energy sources.

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