Green Energy and Technology

Anoop Singh
Deepak Pant
Stig Irving Olsen *Editors*

Life Cycle Assessment of Renewable Energy Sources

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Stig Irving Olsen
Editors

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Springer

Editors
Anoop Singh
New Delhi
India

Stig Irving Olsen
Bagsværd
Denmark

Deepak Pant
PRODEM
Mol
Belgium

ISSN 1865-3529 ISSN 1865-3537 (electronic)
ISBN 978-1-4471-5363-4 ISBN 978-1-4471-5364-1 (eBook)
DOI 10.1007/978-1-4471-5364-1
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2013946320

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

With the advent of modern civilisation and continuously growing human population, there is constant increase in the demand for the energy world over for livelihood and recreational purposes. The major sources of conventional energy derived through petroleum resources and coal reserves are depleting, which have raised the concerns and led to growing global interest in developing alternative sources of energy. National governments also see energy independence as a kind of security for the country. There have been intensive efforts all over the world to explore and exploit the alternative energy sources, such as solar energy, wind energy, bioenergy, etc. Bioenergy largely relies on biomass-based processes for the development of liquid and gaseous fuels, which have often been termed as first generation (ethanol from corn and other starchy sources), second generation (bioethanol from lignocellulosic feedstocks and biodiesel from vegetable oils), third generation (biofuels derived from algae) and fourth generation (biohydrogen). Biofuels derived from renewable materials offer much promise. In addition to serve as alternative source of energy, they also offer potential benefits on environmental impact in comparison to fossil fuels.

For the development of technologically and economically feasible renewable energy process, not only one requires substantial basic R&D data, but must also develop suitable models and integrate them with scale-up data. Yet another important aspect in this regard is life cycle assessment (LCA) study, which should be accomplished for a complete economic, environmental and social sustainability scenario development. LCA studies could involve the production and use of a product or the development of a service or product. In either cases, environmental and economic scenarios must be given due consideration.

The book on 'Life Cycle Assessment of Renewable Energy Sources' provides state-of-the-art information on the LCA studies and scenarios for the renewable energy. The editors have put together a host of highly relevant topics, ranging from the importance of LCA for renewable energy sources, key issues for bio-based renewable energy sources LCA, LCA for the production of biogas, bioethanol, biodiesel from different feedstocks, LCA for wind energy, solar energy, hydropower and comparison of different LCA studies. These aspects have been dealt by the peers.

LCA should involve the elements of life cycle inventory, life cycle impact assessment and interpretation. All these have been achieved in this book by describing the specialty processes and pioneering works. The editors have brought together a pool of expertise to present the state-of-the-art information, which have presented in-depth analysis of the knowledge on various aspects.

Overall, the information provided in this book is highly scientific, updated and would be beneficial for the researchers and practitioner equally; this will be also useful for those entering into this area.

Ashok Pandey
National Institute for Interdisciplinary Science and Technology, CSIR
Trivandrum, India
Editor-in-Chief, Bioresource Technology (Elsevier)

Preface

In recent years, a lot of emphasis has been given to renewable, sustainable and environment friendly energy sources in order to offset the dependence of mankind on conventional and non-renewable sources of energy most of which are fossil-based. However, the plethora of options available today makes it difficult for the users, policy makers as well as the researchers in this area to identify the right source for a specific situation as the usage and implementation depends on a variety of factors such as availability, ease of transportation, maintenance and end-of-life options. Energy and environment are closely interlinked and therefore any alternative energy option brings with it a certain impact on the environment. Several terms such as 'cradle to grave', 'cradle to cradle', 'cradle to gate' are used in this regard to denote the impacts at each stage of a product's life-cycle. This has led to a lack of understanding among the practitioners in this field and often leads to complicated situations where no agreement can be found over one single source of renewable energy. The integrated assessment of all environmental impacts from cradle to grave is the basis for many decisions relating to achieving improved products and services. The assessment tool most widely used for this is the environmental Life Cycle Assessment (LCA).

This book is intended to have three roles and to serve three associated audiences namely, the students and research community who will benefit from the lucid explanation of the LCA aspects of different bioenergy systems, the policy makers who will find it easier to identify the pros and cons of one type of bioenergy systems against another and finally the industries involved as it will give them a feeling about the current loopholes and ways to fix them. New developments in LCA methodology from all over the world have been discussed and, where possible, complemented with real life examples by the renowned experts in the field. Integration of all the recent developments into a new, consistent methodology for each type of renewable energy system has been the main aim for this book. Though we have tried to be very objective in our choice of topics to be covered in this book, some not so common themes might have been missed but which may become important in future which we will try to cover in the second edition of the book. "Importance of Life Cycle Assessment of Renewable Energy Sources" gives an overview of LCA for renewable energy sources, "Key Issues in Conducting Life Cycle Assessment of Bio-Based Renewable Energy Sources" –"Sustainability of (H_2 + CH_4) by Anaerobic Digestion via EROI Approach and LCA Evaluations" discusses the LCA of different types of biofuel systems. "Life-Cycle Assessment of Wind Energy" explores the LCA of wind energy and "Comparing Various Indicators for the LCA of Residential Photovoltaic Systems" deals with photovoltaic systems. "Hydropower Life-Cycle Inventories: Methodological Considerations and Results Based on a Brazilian Experience" explain the LCA aspect of hydropower while "A comparison of Life Cycle Assessment Studies of Different Biofuels" compares the LCA approaches for different renewable energy sources.

A major advantage of this book is that it also provides advice on which procedures should be followed to achieve adequate, relevant and accepted results. Furthermore, the distinction between detailed and simplified LCA makes this book more broadly applicable, while guidance is provided as to which additional information can be relevant for specialised applications.

We sincerely hope that this book will contribute to the necessary transition to environmentally benign and sustainable energy production and consumption.

Anoop Singh
Deepak Pant
Stig Irving Olsen

Acknowledgments

We, the editors would like to thank several people who helped us as we continued to work on this book. We begin by thanking Anthony Doyle from Springer who first approached us with the proposal for the book and helped us crystallise our ideas on the topic. Afterwards Quinn Grace and Christine Velarde took over and provided excellent support with all the administrative work. We also thank all the authors who kindly agreed to provide the chapters and worked with us throughout the process. We are also grateful to the reviewers who took time out of their busy schedule to critically review the chapters of this book and provided very valuable suggestions for their improvements. This book is a labour of love for us since we spent a lot of our weekends and free time on working on it. For this reason alone, our families deserved to be thanked for bearing with us all this while. Anoop and Stig like to thank the management of Technical University of Denmark (DTU), Lyngby, Denmark for their support. Deepak would like to thank the management of VITO especially Dr. Karolien Vanbroekhoven, Programme Manager at Separation and Conversion Technology unit for her unflinching support and encouragement towards this endeavour.

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About the Editors

Dr. Anoop Singh, is a Scientist at Department of Scientific and Industrial Research (DSIR), Ministry of Science and Technology, Government of India. He completed his Doctoral degree in Botany in 2004 from AAIDU, Allahabad, India and his Master's degree in Environmental Sciences in 2001 from GBPU-AT, Pantnagar, India. Before joining DSIR, he worked at Technical University of Denmark, Denmark; University College Cork, Ireland; The Energy and Resources Institute (TERI), New Delhi, India; Indian Agricultural Research Institute (IARI), New Delhi, India; Banaras Hindu University, Varanasi, India; and VBS Purvanchal University, Jaunpur, India. He has visited several European countries and participated in several international conferences. He has published more than 50 research articles in scientific journals (>1,000 citations, h-index 17) and is a member of several scientific communities. He is serving as Editorial board member for a number of journals besides being a reviewer. His research interests are focused on sustainable agriculture, waste management through agriculture, the utilization of industrial, agricultural, and household waste for eco-friendly energy production, renewable energy, and their life cycle assessment (LCA).

Dr. Stig Irving Olsen is an Associate Professor in sustainable production at the section for Quantitative Sustainability Assessment, Department of Management Engineering at the Technical University of Denmark. He obtained his Ph.D. in LCA from Technical University of Denmark in 1997 and a Master of Science in Biology from University of Copenhagen in 1988. Since his Ph.D., his main research area has been in methodology development in LCA, particularly in the life cycle impact assessment of human health impact. During the last years his research has focused more on application of LCA in several technology areas, including renewable energy and nanotechnology.

Dr. Deepak Pant is a Research Scientist at the Flemish Institute for Technological Research (VITO), Belgium, currently working on bioenergy, specifically, the design and optimisation of bioelectrochemical systems for energy recovery from wastewaters and microbial electrosynthesis for production of value added chemicals and fuels through electrochemically driven bioprocesses. He has a Ph.D. in Environmental Biotechnology (2007) from TERI University, New Delhi (India) and has 28 peer-reviewed publications with 950 citations (h-Index 14) and 10 book chapters to his credit. He is involved in several European projects on biomass, biowaste, wastewater treatment and feasibility studies. His research experience lies in industrial wastewater treatment, wasteland reclamation and restoration, biofertilisers, sustainable agriculture, biofuels and bioenergy and life cycle analysis (LCA).

Contributors

Johan Albrecht Faculty of Economics and Business Administration, Ghent University, Tweekerkenstraat 2, 9000 Ghent, Belgium

Jo Dewulf Research Group ENVOC, Ghent University, Coupure Links 653, 9000 Ghent, Belgium

J. Blanco Fernández Department of Mechanical Engineering, University of La Rioja, Logroño, La Rioja, Spain

Shabbir H. Gheewala The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, Thailand; Center for Energy Technology and Environment, Ministry of Education, Bangkok, Thailand

Reinout Heijungs Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands

Nicholas E. Korres 26 Grigoroviou street, Patisia, 11141 Athens, Greece

Luiz Alexandre Kulay University of São Paulo, São Paulo, Brazil

Ruben Laleman Faculty of Economics and Business Administration, Ghent University, Tweekerkenstraat 2, 9000 Ghent, Belgium

Keat Teong Lee School of Chemical Engineering, Universiti Sains Malaysia, Seri Ampangan, Nibong Tebal, 14300 SPS, Pulau Penang, Malaysia

E. Jiménez Macías Department of Electrical Engineering, University of La Rioja, Logroño, La Rioja, Spain

E. Martínez Cámara Department of Mechanical Engineering, University of La Rioja, Logroño, La Rioja, Spain

Flávio de Miranda Ribeiro Pollution Prevention Group—University of Sao Paulo (GP2-USP), Sao Paulo, Brazil

Abdul-Sattar Nizami Center of Excellent in Environmental Studies (CEES), King Abdulaziz University (KAU), P.O. Box 80216, 21589 Jeddah, Saudi Arabia

Iqbal Mohammed Ismail Center of Excellent in Environmental Studies (CEES), King Abdulaziz University (KAU), P.O. Box 80216, 21589 Jeddah, Saudi Arabia

Cynthia Ofori-Boateng School of Chemical Engineering, Universiti Sains Malaysia, Seri Ampangan, Nibong Tebal, 14300 SPS, Pulau Penang, Malaysia

Stig Irving Olsen Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

Deepak Pant Separation and Conversion Technology, Flemish Institute for Technological Research (VITO), Mol, Belgium

Dheeraj Rathore Department of Conservation Biology, School of Biological Science, College of Natural and Mathematical Sciences, University of Dodoma, Dodoma, Tanzania

B. Ruggeri Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

S. Sanfilippo Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

Gil Anderi da Silva Brazilian Life-Cycle Association, Coordinator of Pollution Prevention Group—University of Sao Paulo (GP2-USP), Sao Paulo, Brazil

Anoop Singh Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark, Kongens Lyngby, Denmark; Department of Scientific and Industrial Research (DSIR), Ministry of Science and Technology, Government of India, Technology Bhawan, New Mehrauli Road, New Delhi 110016, India

T. Tommasi Center for Space Human Robotics, Istituto Italiano di Tecnologia, Corso Trento 21, 10129 Turin, Italy

Edi Iswanto Wiloso Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands

Importance of Life Cycle Assessment of Renewable Energy Sources

Anoop Singh, Stig Irving Olsen and Deepak Pant

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

A. Singh (✉) · S. I. Olsen
Department of Scientific and Industrial Research (DSIR), Ministry of Science and Technology, Technology Bhawan, New Mehrauli Road, New Delhi 110016, India
e-mail: apsinghenv@gmail.com

S. I. Olsen
e-mail: siol@dtu.dk

D. Pant
Separation and Conversion Technology, Flemish Institute for Technological Research (VITO), Mol, Belgium
e-mail: deepak.pant@vito.bepantonline@gmail.com

A. Singh et al. (eds.), *Life Cycle Assessment of Renewable Energy Sources*,
Green Energy and Technology, DOI: 10.1007/978-1-4471-5364-1_1,

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).

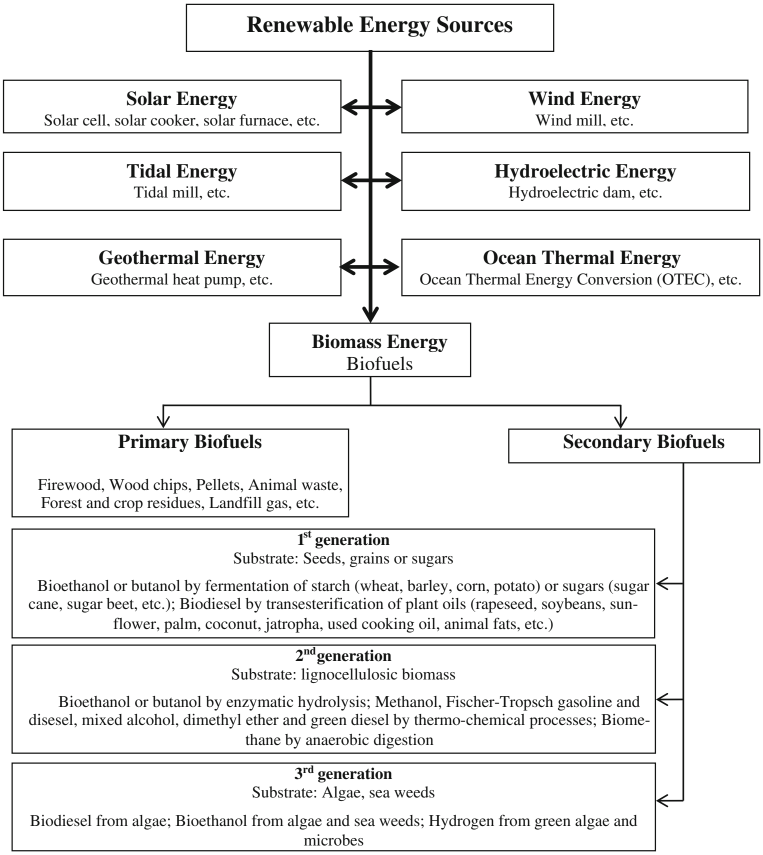

Fig. 1 The most important renewable energy sources

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

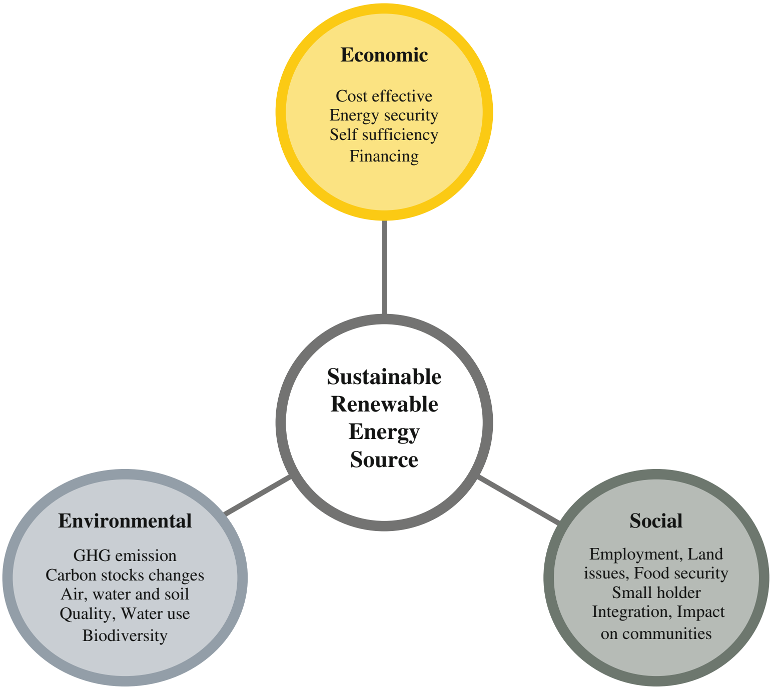

Fig. 2 Economic, social, and environmental aspects of sustainable renewable energy sources (Adapted from IEA 2011; Singh and Olsen 2012)

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

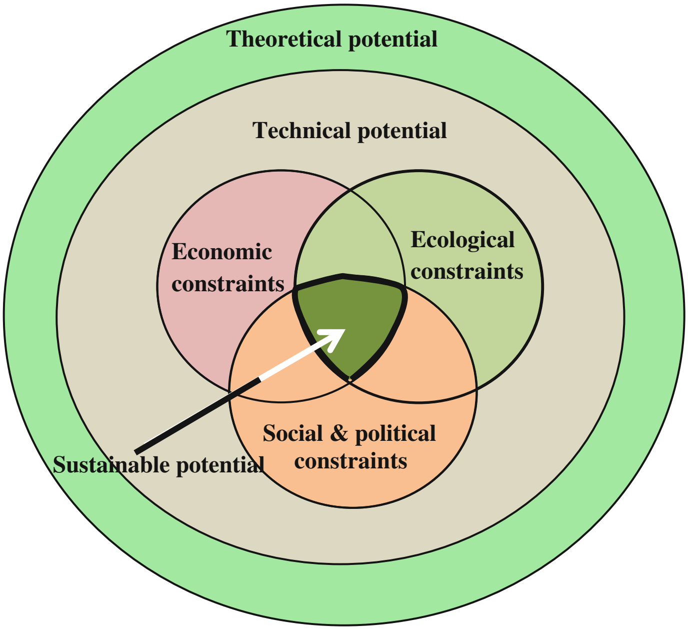

Fig. 3 Schematic illustration of the technical potential and constraints to the sustainable biomass potentials (Adapted from Steubing et al. 2010)

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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Key Issues in Conducting Life Cycle Assessment of Bio-based Renewable Energy Sources

Edi Iswanto Wiloso and Reinout Heijungs

Abstract Although there is an ISO-standardized method for conducting life cycle assessment (LCA) studies, its application to renewable energy sources, in particular to bio-based renewable energy (bioenergy) involving agricultural chains, is not straight forward. There are theoretical and practical issues in goal and scope definition, functional unit, inventory analysis, and impact assessment. The debate between attributional LCA and consequential LCA is, for bioenergy, even more crucial than for ordinary products, especially when it comes to either direct or indirect land-use change. Data are often highly variable, and system boundaries are quite arbitrary. For bioenergy from biomass residues, allocation and recycling provide complications. The treatment of biogenic carbon is of particular interest. The choice of impact categories and the necessity of a regionalized impact assessment are another problem. This chapter provides a systematic overview of these topics.

1 Introduction

Our economy has long been dependent on non-renewable energy carriers, especially on fossil energy. The high dependence on non-renewable energy sources developed over a relatively short period of time. From the middle of the nineteenth century, there was a rapid increase in the use of fossil fuels. These non-renewables replaced wood and soon became the basis of an exponential growth in energy use associated with a number of novel energy-demanding activities (Sørensen 2002). Early man was only capable of causing environmental disturbance on a local scale; however, man has currently achieved a technological level, enabling him to

E. I. Wiloso (✉) · R. Heijungs
Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands
e-mail: wiloso@cml.leidenuniv.nl; ediiswanto@yahoo.com

A. Singh et al. (eds.), *Life Cycle Assessment of Renewable Energy Sources*,
Green Energy and Technology, DOI: 10.1007/978-1-4471-5364-1_2,

convert energy at rates that are responsible for climate change over extended areas. With 81 % of recent global energy use originating from fossil fuels, 6 % from nuclear, and 13 % from renewable energy (IEA-Bioenergy 2009), it is understandable that human societies have recently begun to reconsider the use of renewable sources. In light of this development, we are now, along with other environmental impacts, facing two major problems: depletion of fossil resources and an increase in anthropogenic levels of carbon dioxide.

Alternative options that are available to reduce our dependence on non-renewable sources and simultaneously mitigate climate change are already in development. The use of bio-based renewable energy (bioenergy) is now deemed to be one of the most promising renewable energy alternatives. Reasons typically given for why bioenergy should be promoted are diverse. Bioenergy is considered carbon neutral, it is made from renewable resources, it stimulates the agricultural sector, and it may be produced domestically in many countries, hence diminishing political and economic dependency on other countries (Guinée et al. 2009). However, criticisms have also developed against biofuels, particularly on their role in the food price spikes and the nature of land-use change. A specific example of this case is the maize to bioethanol for transportation fuel in the United States that induced land-use impact, direct and indirect (Harvey and Pilgrim 2011). WRI (2005) indicated that land use (18.2 %) and agriculture's (13.5 %) contribution to greenhouse gas emissions (GHGs, including N_2O and CH_4 in addition to CO_2) are globally estimated to be at least twice the amount of the total emissions from global transport (13.5 %). This assessment indicates the importance of the potential contribution of the land-use aspect to the overall environmental burden of bioenergy systems. Major activities related to these land-use-related impacts are deforestation that releases carbon dioxide from burning or decomposing biomass and oxidizing uncovered humus. In addition to other impact categories such as biodiversity loss and soil quality degradation, all these emissions may negate any GHG benefits of biofuel systems for decades to centuries (Tilman et al. 2009). In this regard, these same authors proposed that biofuels should receive policy support as substitutes for fossil energy only when they make a positive impact on four important objectives: energy security, GHG emissions, biodiversity, and the sustainability of the food supply.

Bioenergy is presently the largest global contributor (77 %) to renewable energy and has contributed significantly to the production of heat, electricity, and fuels for transport (IEA-Bioenergy 2009). Therefore, in the following parts of this chapter, discussion will be focused on bioenergy as the dominant fraction of renewable energy. The main feedstocks for bioenergy are biomass residues from forestry, agriculture, and municipal waste. Only a small portion of sugar, grain, and vegetable oil are used for the production of liquid biofuels (IEA-Bioenergy 2009). There are many technological routes available to convert biomass feedstock into final bioenergy products. Several conversion technologies have been developed to adapt to the unique physical nature and chemical composition of various biomass feedstocks. These include direct combustion (heat), co-firing/combustion (heat/power), gasification (heat/power), anaerobic digestion (heat/power/fuel:

methane), fermentation (fuel: bioethanol), trans-esterification (fuel: bioediesel), and photosynthesis (fuel: hydrogen) (IEA-Bioenergy 2009). These various conversion technologies will dictate overall environmental performances. For example, ethanol production through biochemical or thermochemical conversions is expected to result in different levels of decreasing GHG emissions. However, these conversion-related differences are likely to be small in relation to those associated with feedstock production (Williams et al. 2009). In addition, emissions of methane or nitrous oxide from agricultural field and indirect land-use change may contribute to a more complicated overall picture (Cherubini and Strømman 2011). Side and rebound effects, as well as market mechanisms, of large-scale production of biofuels also affect food markets, resource scarcity, and environmental quality, while these factors are often left out in a sustainability assessment (Guinée et al. 2011; van der Voet et al. 2010). Moreover, bioenergy systems may involve a unit process with input–output flows, which often make it difficult to differentiate between economic (products) and elementary (resource use or emissions) flows.

Recently, there have been tremendous numbers of LCA studies describing bioenergy in order to support policy making. The growing debate on bioenergy and other bio-based products contributed to the acceleration of the development of LCA methodology. However, it is difficult to draw general conclusions from the set of studies due to large variations in outcomes. Sources of these variations include real-world differences, data uncertainties, incompleteness of included impacts, and methodological choices (van der Voet et al. 2010). More specifically, the methodological choices are related to the selection of a functional unit, system boundary, land-use aspects, biogenic carbon, treatment of multi-functional processes, data variability, and regionalized impact assessment (Cherubini and Strømman 2011; van der Voet et al. 2010; Guinée et al. 2009; Finnveden et al. 2009). This indicates that bioenergy poses more methodological challenges than other renewable energy. Moreover, these issues are insufficiently comprehensively addressed by current LCA studies.

This chapter is aimed at providing a systematic overview on the above-mentioned key issues in conducting LCA of bioenergy. Detailed comparison of methodological choices among different LCAs of bioenergy systems can be found in recent surveys such as those of Cherubini and Strømman (2011), van der Voet et al. (2010), Wiloso et al. (2012), and Singh et al. (2010). The structure of this chapter will follow the first three phases of the LCA framework (ISO 2006), including goal and scope definition, inventory analysis, and impact assessment as follows:

- Goal and scope definition:
  - Attributional and consequential LCA
  - Functional unit
- Inventory analysis:
  - System boundary
  - Land use and land-use change

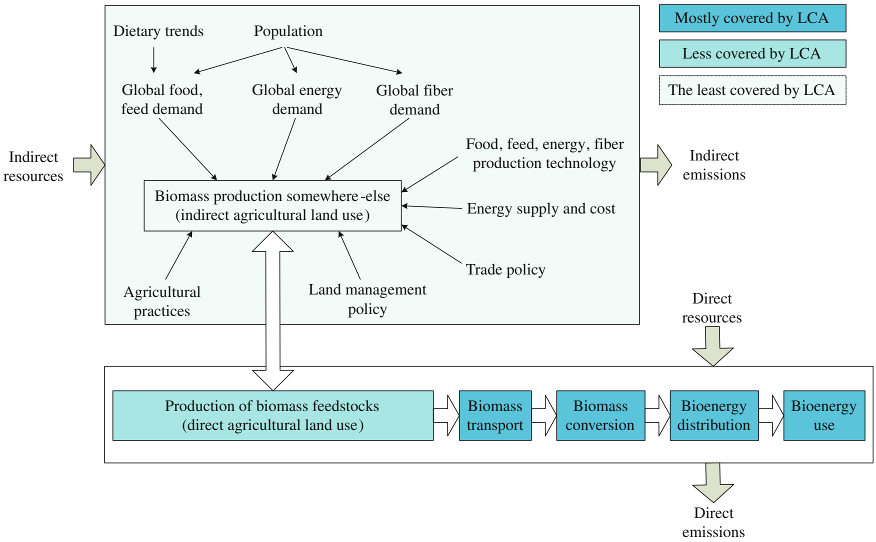

Fig. 1 Direct and indirect effects of a generic bioenergy system (modified from Sheehan 2009). Different shading intensity indicates present coverage in LCA studies

  – Biogenic carbon
  – Treatment of multi-functional processes
  – Data variability

- Impact assessment:

  – Impact categories
  – Regionalized impact assessment

A generic bioenergy system that spanned from a cradle-to-grave boundary is presented in Fig. 1. The system covers biomass production, biomass transport, biomass conversion, and bioenergy distribution and use. In the upstream chain, the production of biomass feedstock is connected with agricultural land use, direct and indirect. The association of the biomass feedstock with land-use aspects is currently recognized as the central feature in conducting an LCA of bioenergy systems.

2 Goal and Scope Definition

Questions related to the overall objective of LCA studies should be formulated in the goal and scope definition. The goal is closely related to the context in which an LCA study is done, and the scope includes making choices concerning the methodology to use in the subsequent modeling (Baumann and Tillman 2004).