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Bioenergy, Food Security and Poverty Reduction:

Mitigating tradeoffs and promoting synergies along the Water-Energy-Food Security Nexus

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Abstract

Modern bioenergy is a core ingredient of sustainable economic development as it plays an important role in poverty reduction and green growth. This makes bioenergy innovations critical, especially in developing countries where many households and rural communities rely on traditional bioenergy. Managing the multiple tradeoffs among bioenergy use, agricultural productivity, and ecosystem functions is a major development challenge. Addressing this challenge requires the identification of the drivers, tradeoffs and impacts of bioenergy production, trade and use in the Water, Energy and Food Security Nexus. The key objective of this paper is to provide an analytical framework and assess the track record of policy actions to stimulate modern bioenergy innovation in order to achieve multiple-win outcomes in terms of poverty alleviation, improved health and gender empowerment and environmental sustainability. We begin by describing the global trends and drivers in bioenergy production, trade and use. Secondly, we review the state of the art on impacts and links of bioenergy with the other Nexus components. Thirdly, we suggest a conceptual framework for evaluating the synergies and tradeoffs of bioenergy with other bioeconomic and economic activities along the Nexus. Follow-up empirical research at household and community levels in several developing countries will be based on this framework. Finally, a discussion on the conceptual framework is enriched by insights on the relevant actors, the tools and mechanisms specific to these actors for catalyzing innovations in the bioenergy for development.

Keywords: bioenergy, poverty reduction, food security, decentralized energy, WEF Nexus tradeoffs and synergies, households and communities, innovations

Contents

List of Abbreviations

APEC	Asia-Pacific Economic Cooperation
BEFSCI	Bioenergy and Food Security Criteria and Indicators
BMU	German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety
BMZ	German Federal Ministry for Economic Cooperation and Development
Btu	British thermal unit
CGE	Computable general equilibrium
CHP	Combined heat and power
CO_2	Carbon dioxide
DALYs	Disability-adjusted life years
EBTC	European Business and Technology Centre
EIA	Energy Information Administration
EJ	Exajoule
EPI	Earth Policy Institute
FAOSTAT	The Food and Agriculture Organization Corporate Statistical Database
FDI	Foreign direct investment
GBP	Global Bioenergy Partnership
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule
GRID Arendal	Global Resource Information Database, Arendal
GTAP	Global Trade Analysis Project
ha	Hectare
IEA	International Energy Agency
kWh	Kilowatt hour
MFED	Ministry of Finance and Economic Development of Ethiopia
mln	Million
MNRE	Ministry of New and Renewable Energy of India
MoWE	Ministry of Water, Irrigation & Energy of Ethiopia
NIE	New Institutional Economics
NREL	National Renewable Energy Laboratory, U.S. Department of Energy
OECD	Organisation for Economic Co-operation and Development
PJ	Petajoules
PPPs	Private-public partnerships
PTEM	Physical-technical-economic models
R & D	Research and development
REEEP	Renewable Energy and Energy Efficiency Partnership
REN21	Renewable Energy Policy Network for the 21st century
S & T	Science and technology
SARE	Sustainable Agriculture Research and Education
TWh	Terawatt hour
UN	United Nations

UNEP	United Nations Environment Programme
WHO	World Health Organization

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Executive Summary

Modern bioenergy is a core ingredient of sustainable economic development and plays an important role in poverty reduction and green growth.

Bioenergy is derived from woody biomass, agro-residues, energy crops, food crops, agro-industrial and municipal solid wastes and other biological resources. Bioenergy is a major sector of the bioeconomy - the aggregate of all industrial and economic sectors and their associated services which produce, process or in any way use biological resources. In fact, in most developing countries, bioeconomy is the largest cluster of sectors in terms of its share in Gross Domestic Product (GDP) and employment.

For these reasons, bioenergy innovations are critical, especially in developing countries where many households and rural communities rely on traditional bioenergy. Recent estimates by the International Energy Agency (2013) indicate that in 2011 about 2.64 billion people (38% of the global population) relied on biomass, mostly fuel wood, for cooking. For developing countries alone, the share of biomass energy used for cooking and heating is much higher. About 79% of Sub-Saharan African population and 51% of people in developing Asia rely on traditional biomass energy. However, the traditional uses of biomass for heating and cooking are low in energy efficiency, may pose health hazards due to indoor air pollution, and have a high opportunity cost of family, especially female, labor. To illustrate, the indoor smoke from the use of traditional fuels is estimated to claim about 2.5-4 mln lives annually (Lim & Seow, 2012). Moreover, bioenergy is a crucial energy source for marginalized and rural areas, especially “energy islands”, i.e. regions with decentralized energy supply, thus placing it at the forefront of efforts on poverty reduction and sustainable economic development. In spite of this, the use of modern bioenergy technologies by households and communities remains quite low in developing countries, especially in Sub-Saharan Africa.

In this context, increasing global population and growing demands for food, feed, energy, water, land and other resources further intensify the competition and trade-offs among different uses and sectors. For example, food and biofuel production compete for land and water, which also leads to increased and more volatile food prices, affecting the food security of the poorest rural and urban households most negatively. Competition for water may cause conflicts, particularly when large scale bioenergy competes with local water demand for food crop production in water-scarce areas. On the other hand, modern bioenergy development is believed to have a considerable potential to reduce poverty, for instance by creating employment opportunities, which raise incomes and help mitigate possible negative effects of bioenergy development on food security. Although modern bioenergy development is expected to positively contribute to environmental sustainability through helping in “decarbonizing” the energy production, the life cycle assessments of bioenergy production do not always point at net positive carbon balances. Specifically, over the last decade, biofuel production has significantly contributed to direct and indirect global land use change, including through deforestation. In South East Asia, for instance, expansion of oil palm was found to lead to fewer species, habitat fragmentation and pollution (Fitzherbert et al., 2008). On the contrary, the production of biofuels from waste biomass and from energy crops cultivated in degraded or abandoned agricultural lands is believed to offer sustainable reductions in GHG emissions.

Bioenergy potentials need to be assessed in the context of the broader energy system, the food and agriculture system, and the water use systems, i.e. in a Nexus framework among these interrelated components. The Water-Energy-Food Security Nexus, applied in this research, is a conceptual framework that recognizes the interconnection of these three broad sectors and seeks to develop joint solutions that mitigate the tradeoffs and promote synergies among them.

What is needed is a “leapfrogging” to a more knowledge-based bioeconomy with more efficient and cleaner sources of energy for households and communities in the developing world. One potential option for remote off-grid locations is the development of decentralized energy systems. For example, decentralized community-operated mini-grids and household energy systems using locally available energy resources (modern bioenergy, solar, wind and micro-hydropower) can be an important tool for improving the access to energy by such off-grid communities. Moreover, the access to electricity through decentralized mini-grids was found to facilitate a wider fuel switching to modern bioenergy (Heltberg

2004). Specifically, in Assam, India, access to electricity was found to increase literacy rates from 63.3% to 74.4% (Kanagawa and Nakata 2007); similarly, in Brazil, rural electrification was found to reduce poverty by 8% and the Gini coefficient of inequality from 0.39 to 0.22 (Pereira et al. 2008). At the same time, "leapfrogging" in energy would also necessitate a "leapfrogging" in institutions to be successful. Thus, the effective contribution of modern bioenergy to access and security of energy depends not only on biomass and technology, but also on the institutional and organizational arrangements and related actors. Hence, deeper knowledge of stakeholder environment and of the incentives and constraints of key stakeholders is important for accurate analyses of bioenergy development and its impacts.

At the same time, the research on the impacts of bioenergy development on the poor households and communities has some important gaps. Firstly, the tradeoffs and synergies of bioenergy production with sustainable land management, water and food security need to be studied more extensively using quantitative approaches. Secondly, more research is also needed on evaluating the drivers and mechanisms of technical and institutional innovations in bioenergy development at household and community levels. This includes institutional changes, such as determinants of collective action among households through cooperation in the establishment of decentralized community-managed energy grids. Thirdly, the impacts of traditional use of bioenergy on health and labor productivity are considerable, but remain highly under-researched. Besides, bioenergy development is expected to have gender-differentiated effects, which are not yet thoroughly analyzed. For example, women using traditional biomass for cooking were found to be 3.3 times more likely to suffer from chronic bronchitis and emphysema, than those who use cleaner alternatives, such as electricity or gas (Rehfuess et al. 2006). Finally, there is a continuing need to identify feasible and efficient policies to catalyze modern bioenergy development among households and communities in developing countries.

Studying bioenergy development in a Water-Energy-Food Security Nexus framework can thus help us better understand its real opportunities and potential constraints. The present paper proposes such a Nexus-based analytical framework. This trans-disciplinary framework is considered to be more appropriate for analyzing jointly the multi-dimensional aspects of bioenergy, their inter-linkages and feedback mechanisms with other economic activities of households and communities, rather than looking into bioenergy development in isolation.

Zusammenfassung

Moderne Bioenergie ist ein unverzichtbarer Bestandteil nachhaltiger wirtschaftlicher Entwicklung und spielt eine wichtige Rolle in Armutsbekämpfung und „grünem Wachstum“.

Bioenergie wird aus Brennholz, landwirtschaftlichen Rückständen, Energie- und Nahrungspflanzen, agrarindustriellen und kommunalen Abfällen und anderen biologischen Ressourcen gewonnen. Sie ist ein Hauptsektor der Bioökonomie, worunter alle Sektoren und zugehörigen Dienstleistungen fallen, in denen Biomasse produziert, weiterverarbeitet oder in einer anderen Form genutzt wird. In vielen Entwicklungsländern gilt die Bioökonomie als das größte Cluster an Sektoren, gemessen an ihrem Anteil am Bruttoinlandsprodukt und der Gesamtbeschäftigung.

Aus diesem Grund sind Innovationen in der Bioenergie von großer Bedeutung, insbesondere in Entwicklungsländern, wo sie für viele Haushalte und Gemeinschaften im ländlichen Bereich die einzige Energiequelle darstellt. Aktuellen Schätzungen der Internationalen Energieagentur (2013) zufolge nutzten in 2011 etwa 2,6 Milliarden Menschen, oder 38% der Weltbevölkerung, Biomasse (zumeist Brennholz), um zu kochen. In Entwicklungsländern allein ist der Anteil an Bioenergie als häusliche Energiequelle weitaus höher, mit 79% der Bevölkerung in Sub-Sahara Afrika und 51% in Asien. Die traditionelle Art der Verbrennung von Biomasse ist jedoch oftmals ineffizient, stellt hohe Opportunitätskosten dar, etwa durch das zeitaufwändige Sammeln von Feuerholz, und birgt bei Nutzung in Räumen ein Gesundheitsrisiko. So kostet der Rauch jährlich weltweit etwa 2,5 – 4 Mio. Menschen das Leben (Lim & Seow, 2012). Zudem ist Bioenergie eine unverzichtbare Energiequelle für marginalisierte und ländliche „Energieinseln“, d.h. Gegenden mit dezentraler Energieversorgung. Sie ist daher ein integraler Bestandteil aller Bemühungen zur Armutsbekämpfung und nachhaltiger wirtschaftlicher Entwicklung. Dennoch bleibt die Nutzung moderner Bioenergietechnologien in Entwicklungsländern, insbesondere in Sub-Sahara Afrika, auf niedrigem Niveau.

Die stetig anwachsende Weltbevölkerung und eine steigende Nachfrage nach Nahrung, Viehfutter, Energie, Wasser und Land verstärkt den Wettbewerb zwischen den verschiedenen Sektoren um die Nutzung von Ressourcen. Lebensmittel und Biokraftstoffe etwa konkurrieren um die knappen Ressourcen Land und Wasser – dies führt zu steigenden und stärker schwankenden Preisen für Essen, was wiederum die Ärmsten, sowohl in der Stadt als auch auf dem Land, am stärksten betrifft. Zudem verursacht Wettbewerb um Wasser politische und gewaltsame Konflikte, insbesondere wenn groß angelegte Biokraftstoffprojekte trotz herrschender Wasserknappheit mit der Nutzung von Wasser für die Nahrungsmittelproduktion konkurrieren. Auf der anderen Seite wird mit der Entwicklung moderner Bioenergie die Hoffnung verbunden, Armut zu reduzieren, etwa durch die Schaffung von Arbeitsplätzen. Obwohl erwartet wird, dass die Entwicklung moderner Bioenergie durch die „Entkarbonisierung“ der Energieproduktion zu ökologischer Nachhaltigkeit beiträgt, deuten Untersuchungen nicht immer auf eine positive Bilanz des Kohlenstoffverbrauchs hin. Über das letzte Jahrzehnt haben ein erhöhter Energiebedarf und ein Anstieg der Produktion von Bioenergie signifikant zu direktem und indirektem Landnutzungswandel beigetragen, unter anderem durch Abholzung von Wäldern. In Südostasien hat die Ausweitung von Palmölplantagen zu einem Rückgang der Artenvielfalt, einer Zerschneidung des Lebensraumes und zu Umweltverschmutzung geführt (Fitzherbert et al., 2008). Dennoch verspricht man sich von der Produktion von Biokraftstoffen aus Biomasse und aus Energiepflanzen, die auf abgenutztem oder verlassenem landwirtschaftlichem Land angebaut werden, einen nachhaltigen Rückgang von Treibhausgasemissionen.

Der in dieser Forschung angewandte Nexus um Wasser-Energie-Ernährungssicherheit setzt den konzeptionellen Rahmen, welcher der Vernetzung dieser drei Sektoren Rechnung trägt und nach Lösungen sucht, die Synergien zwischen ihnen zu fördern und Zielkonflikte zu verringern.

Notwendig ist ein „Überspringen“ in eine wissensbasierte Bioökonomie, um Biomasse mithilfe neuer Technologien effizienter und besser zu nutzen. Eine mögliche Option für abgelegene und nicht an das Netz angebundene Gegenden ist die Weiterentwicklung dezentraler Energiesysteme. So können gemeinschaftlich betriebene Mini-Stromnetze sowie Energieproduktion einzelner Haushalte mit lokal verfügbaren Ressourcen (Bio-, Solar-, Wind- und Mikro-Wasserenergie) den Zugang zu Energie in solchen Gegenden deutlich verbessern. Darüber hinaus wurde dem Zugang zu Elektrizität durch dezentrale Mini-

Netze eine Reihe positiver Einflüsse nachgewiesen: Etwa wurde die Umstellung auf moderne Bioenergie, also auf Biokraftstoffe, erleichtert (Heltberg 2004), im indischen Bundesstaat Assam stieg die Alphabetisierungsrate von 63,3% auf 74,4% (Kanagawa and Nakata 2007) und in Brasilien wurde Armut um 8% reduziert und der Gini-Koeffizient sank von .39 auf .22 (Pereira et al. 2008). Gleichzeitig erfordert ein erfolgreiches „Überspringen“ in Energietechnologien auch ein „Überspringen“ in Institutionen. Der effektive Beitrag moderner Bioenergie zu Energiesicherheit und -zugang hängt auch vom institutionellen und organisatorischen Rahmen ab sowie von betroffenen Akteuren. Für eine genaue Analyse der Auswirkungen der Entwicklung von Bioenergie ist daher mehr Wissen über Anreize und Einschränkungen der wichtigsten Stakeholder nötig.

Viele Fragen zu den Wirkungen der Weiterentwicklung von Bioenergie sind noch unbeantwortet. Erstens, müssen die Wechselwirkungen und Synergien zwischen Bioenergieproduktion und nachhaltigem Landmanagement, Wasser und Ernährungssicherheit mithilfe quantitativer Methoden besser erforscht werden. Zweitens, müssen Faktoren und Mechanismen technischer und institutioneller Innovation auf Ebene der Haushalte und Gemeinschaften untersucht werden. Dazu gehört die Frage nach Einflussgrößen institutionellen Wandels, beispielsweise in Form von kollektivem Handeln von Haushalten in der Errichtung und Organisation eines gemeinschaftlich betriebenen, dezentralen Energienetzes. Drittens, ist der Einfluss traditioneller Nutzung von Bioenergie auf die Gesundheit zwar erheblich, aber nicht in ausreichendem Maße erforscht, was ebenso für Gendereffekte gilt. So sind einer Studie zufolge Frauen, die nach traditioneller Art mit Biomasse kochen, 3,3 mal so anfällig eine chronische Bronchitis oder ein Emphysem zu erleiden, wie Frauen, die sauberere Alternativen wie Elektrizität oder Gas verwendeten (Rehfuess et al. 2006). Viertens, und schließlich, müssen durchführbare und effiziente politische Maßnahmen identifiziert werden, welche die Entwicklung moderner Bioenergie von Haushalten und Gemeinschaften in Entwicklungsländern fördern.

Die Bioenergieforschung im Rahmen des Nexus Wasser-Energie-Ernährungssicherheit kann daher dabei helfen, Chancen sowie Grenzen besser zu verstehen. Dieser Beitrag schlägt einen solchen Nexus-basierten analytischen Rahmen vor. Dieser trans-disziplinäre Rahmen ist geeignet, die mehr-dimensionalen Aspekte von Bioenergie und die gegenseitigen Einflüsse mit anderen ökonomischen Aktivitäten gemeinsam zu analysieren, anstatt Bioenergie isoliert zu betrachten.

1 Introduction

It is now widely recognized that sustainable development depends on secure and safe availability of food, water and energy (Ki-Moon 2011). At the same time, industrial raw materials are increasingly based on renewable resources. This puts biomass and bioenergy, and, hence, the bioeconomy at the center of sustainable economic development (BioÖkonomieRat 2009, 2012, Box 1).

Bioenergy potentials to contribute to sustainable development need to be assessed in the context of the broader energy system, the food and agriculture system, and the water use systems, i.e. in a Nexus framework among these interrelated components. This paper provides a review of the dynamics in bioenergy development, and explores their economic drivers. The paper identifies the major impacts of bioenergy development on the national energy sectors, and on households and communities in developing countries, and presents a conceptual framework that can guide further research on bioenergy for development.

Box 1. Definitions of biomass, bioenergy and bioeconomy

Biomass is a broad term defining all types of biological resources used for or processed into energy, food, feed, or any other bio-based products (BioÖkonomieRat 2009, 2012; McKendry 2002).

Bioenergy is the energy derived from woody biomass harvested from forest (fuel wood, charcoal, and residues), energy crops (for example, jatropha, castor oil plant, palm, etc), food crops (vegetable oil, maize, cassava and others), agro-residues (animal manure and crop residues), agro-industrial and municipal solid wastes and other biological resources (Kaygusuz 2010, Don et al. 2012, Edmonds et al. 2012). Some of these resources are directly used for energy for such services as residential cooking and heating. Advanced technologies may help transform these resources into, the so-called, modern types of bioenergy (biodiesel, bioethanol, biogas, electricity and others), which are more widely utilized in the transportation and industrial sectors (Ackom et al. 2013, Maltsoglou et al. 2013). Bioenergy is, typically, the second most important sector, after food and feed production, of the bioeconomy in many countries, followed by forestry and wood products.

Bioeconomy is defined, more comprehensively, as the aggregate of all industrial and economic sectors and their associated services which produce, process or in any way use biological resources (BioÖkonomieRat 2009, Pellerin and Taylor 2008, Arundel and Sawaya 2009, Kircher 2012). Indeed, in most developing countries, bioeconomy is the largest cluster of sectors in terms of its share in Gross Domestic Product (GDP) and employment (von Braun 2012).

1.1 Scope for innovation

Several factors require development and wide-scale application of bioenergy innovations. Globally, the population is projected to grow to about 9.6 billion by 2050 (UN 2013). In combination with rising incomes, this requires substantial increases in food, feed and energy production, putting more pressure and increasing the competition for land, water and other resources (von Braun 2007, Harvey and Pilgrim 2007). Moreover, mitigation of climate change calls for more accelerated transition to CO_2-neutral sources of energy (Höök and Tang 2013).

Bioenergy development offers potential gains, but the extent of its contribution to the global energy production and sustainable development is debated (Berndes et al. 2003, Slade et al. 2011). It is recognized that bioenergy alone may not be able to fully supply the global energy demand any time soon (Dornburg et al. 2010). However, bioenergy remains a relevant, crucial and significant energy source for marginalized and rural areas, especially “energy islands” (i.e., regions with decentralized energy supply) (Driesen and Belmans 2005), thus placing it at the forefront of efforts on poverty reduction and sustainable economic development.

Bioenergy innovations are especially needed in developing countries because of their higher reliance on bioenergy as the main energy source (Gerber 2008, IEA 2013). There is a critical need to increase the efficiency of bioenergy use with new technologies, i.e. a leapfrogging into a more knowledge-based bioeconomy needs to be explored (von Braun 2012). Traditional uses of biomass for heating and cooking in many developing countries are low in energy efficiency, may pose health hazards due to indoor air pollution, and have a high opportunity cost of family labor (Ezzati and Kammen 2002, Feng et al. 2009). To illustrate, the indoor smoke from the use of traditional fuels is estimated to claim about 2.5-4 mln lives annually at global level (Lim & Seow 2012). Therefore, technological advancements in bioenergy use are also necessary for reducing related human health and productivity losses (Ezzati and Kammen 2002).

1.2 Research gaps and practical relevance

The research on the impacts of bioenergy development on the poor households and communities has some important gaps. Firstly, the tradeoffs and synergies of bioenergy production with sustainable land management, water and food security by households and communities in developing countries need to be studied more extensively using quantitative approaches. Secondly, more research is also needed on evaluating the drivers and mechanisms of technical and institutional innovations in bioenergy development at household and community levels, including institutional changes, such as determinants of collective action among households in joint bioenergy development, for example, through cooperation in the establishment of decentralized community-managed energy grids. Thirdly, the impacts of traditional use of bioenergy on health and labor productivity are considerable, but received so far only a scant attention in the literature (Duflo et al. 2008). Moreover, bioenergy development is expected to have gender-differentiated effects, which are not yet thoroughly analyzed. Finally, there is a continuing need to identify feasible and efficient policies to catalyze modern bioenergy development among households and communities in developing countries.

Reviewing the relevant literature, this working paper presents the global dynamics in bioenergy development (Chapter 2), the state of the art in economic research on bioenergy, with emphasis on household and community levels in the developing countries (Chapter 3), the conceptual framework that can guide further research on bioenergy for development (Chapter 4), and the role of key actors and stakeholders for bioenergy development (Chapter 5). The final section presents the conclusions and the outlook for the future related research.

2 Global dynamics of bioenergy development

2.1 Past trends and current situation in bioenergy use, production and trade

Bioenergy is derived from solar radiation and stored in plants in the form of biomass (Heaton et al. 2004). It is the primary source of energy in many developing countries (Demirbas 2009), where biomass is, usually, used directly without undergoing any further processing. The so-called modern bioenergy comes from further processing of biomass into many new forms, such as liquid transportation fuel or electricity (ibid.). Depending on the availability of advanced technologies, all biomass can be used either directly as energy or processed into modern bioenergy. Bioenergy sourced through the photosynthesis by plants is considered to be less economically efficient for producing renewable energy as the rate of conversion of the total solar energy received to usable energy output is relatively low (Barber 2009). However, one advantage of bioenergy, compared to other renewable energy sources, is its higher convenience for storage and transportation (McKendry 2002). It can be produced and used everywhere where biomass can be produced. Moreover, bioenergy technologies are developing rapidly. Whereas the first and second generation of bioenergy types, such as ethanol and biodiesel, were produced from food-based crops, such as sugar beet, wheat, maize, soy, rapeseed, vegetable oil, etc., the third and fourth generation of biofuels make use of algal biomass, artificial photosynthesis or are developed using advanced bio-chemical processes, and do not directly compete with food production (Kagan 2010)..

Biomass provides about 10% of the total 500 EJ of annual global energy use (IEA 2008), with other 80% coming from fossil fuels, and another 10% from all other sources (Goldemberg and Johansson 2004). Recent estimates by the International Energy Agency (IEA) (2013) indicate that in 2011 about 2.64 billion people (about 38% of the global total) relied on biomass, mostly fuel wood, for cooking. For developing countries alone, the share of biomass energy used for cooking and heating is much higher. About 79% of Sub-Saharan African population and 51% of people in developing Asia rely on traditional biomass energy (Table 1). India accounts for about 31% of global population who still rely on traditional biomass energy and Sub-Saharan countries account for another 26%.

A major source of bioenergy in most developing countries is fuel wood. The global production of fuel wood (including wood for charcoal) constituted about 1.8 km^3 in 2009 (FAOSTAT 2011) and increased by about 1.3% from 2004, where Asia contributed 42%, followed by Africa (32%) and Latin America and Caribbean (15%) (FAOSTAT 2011, Figure A-1 in the annex). Lamers et al. (2012) estimated that the global trade of wood had increased from about 56 to 300 PJ between 2000 and 2010 and the trade of wood pellets has also grown at a high rate, from 8.5 to 120 PJ during the same period. EU is the largest wood pellet producer (ibid.).

The other two most important and modern forms of bioenergy are bioethanol and biodiesel, which are also referred to as biofuels and are predominantly used in the transportation sector. In 2010, 110 bln liters of these biofuels were traded in the global energy market (OECD-FAO 2011a, 2011b). The world's total biofuel production experienced a sharp increase between 2000 and 2010 (Figure A-2), and the production of both types of biofuels is predicted to grow further within the coming decade, by 68% for bioethanol (OECD-FAO 2011b), and by 138% for biodiesel (OECD-FAO 2011a). Likewise, there has been an exponential growth in the biofuels trade from 2000 to 2009, with traded biodiesel increasing twenty-fold, and bioethanol trade increasing by 3.5 times (Lamers et al. 2011, OECD-FAO 2011a, 2011b). Global bioethanol production is dominated by the US (63%) and Brazil (24%), together accounting for 87% of the global bioethanol production in 2011, whereas the production of biodiesel is less concentrated, with USA, Germany, Argentina and Brazil as leading producers (see Tables A-1 and A-2, respectively, in the Annex). These countries are also accounting for the largest share in the biofuels trade, where USA and EU are the net importers, and Argentina and Brazil are the main exporters (Lamers et al. 2011).

Table 1. The population relying on traditional use of biomass for cooking in 2011

Region	Population relying on traditional use of biomass (in mln)	Percentage of population on traditional use of biomass
Developing countries	2,642	49
Africa	696	67
Sub-Saharan Africa	695	79
Ethiopia	87	95
Nigeria	122	75
South Africa	6	13
Developing Asia	1,869	51
India	818	66
Pakistan	112	63
China	446	33
Latin America	68	15
Brazil	12	6
Middle East	9	4
World	2,642	38

Sources: IEA (2013), Rehfuess et al. (2005)

Despite the increasing production, the prices of ethanol and biodiesel have also increased between 2005 and 2010 (OECD-FAO 2011a, 2011b), from USD 35 per barrel to about USD 58 for biodiesel and from USD 87 to USD 119 for ethanol (Figure A-3).

The electricity generation with bioenergy, using various technologies such as combined heat and power (CHP), co-firing, cogeneration and biogas, has emerged as a promising option for complementing the fossil sources-based diesel generation (Evans et al. 2010, Dasappa 2011). For instance, in 2010, globally, a total of 280 TWh of electricity, i.e. 1.5% of world electricity generation was produced from biomass, alongside with 8 EJ of bioenergy for heat utilized in the industry (IEA 2012). IEA's technological roadmap projects that by 2050, bioenergy could provide 3100 TWh of transmittable and, in many cases, flexible electricity, meeting about 7.5% of the world electricity demand (ibid). The electricity generation from biomass is still predominantly concentrated in the countries of the Organization for Economic Co-operation and Development (OECD), but China and Brazil are increasingly catching up (Demirbas et al. 2009).

The production and use of renewable energy sources, in general, have also been expanding over the last decade (Figures A-4 and A-5). In this regard, there is a need to evaluate the substitutability of bioenergy and other renewable energy types for fossil fuel in the context of technological options and demand characteristics. Bioenergy has a potential for substituting fossil fuels in almost all end use sectors because of its versatility (Luderer et al. 2013). Versatility implies (i) multiple-fuel generation from biomass, including heat, gaseous, solid, liquid transportation fuel and electricity, (ii) its easy transportability and marketability, and (iii) generation of other non-energy products. Other renewable energy types such as hydropower, geothermal and wind energy are used to generate only the electrical power or heat. Solar energy can be used for generating electricity (including charging batteries) and heating. The solar charging systems can substitute fossil fuels in transportation (cars, planes), but the technology is at an early stage and still expensive.

2.2 Developing and emerging countries in modern bioenergy development

2.2.1 Africa

Despite its substantial untapped renewable energy potential, Africa is lagging behind in modern energy production, utilization and trade (Maltsoglou et al. 2013). However, an increase in the global demand for biomass and bioenergy may help develop Africa's potential in bioenergy. This is because of the resource advantage, specifically land, which has already started attracting investments for bioenergy production (International Land Coalition 2013). For instance, Alexandratos (1995) estimated that Africa has about 750 mln ha of unused land suitable for agriculture. Various estimates exist on the potential of energy production from biomass in Africa, ranging from 134 EJ to 317 EJ today (Smeets et al., 2004; Hoogwijk, 2004) and up to 410 EJ by 2050 (Smeets at al., 2007), where different assumptions are made on increased productivity and availability of land. However, there are growing debates on the issue of the so called "unproductive" land availability in the continent and the impact of bioenergy on local resources such as water availability, soil quality, environment and biodiversity, with many environmental externalities under scrutiny.

The development of modern bioenergy requires substantial investments, while most African countries do not yet have established policies to provide the necessary guidance (Maltsoglou et al. 2013). Moreover, due to limited internal demand for transportation biofuels, most of the potential production in transportation biofuels would need to be oriented towards export markets (ibid.). Also, the foreign investments into bioenergy development in Africa have lately been constrained due to global financial crises, unrealized expectations from jatropha production (Iiyama et al. 2013), and major advancements in hydraulic fracturing in shale gas mining, making bioenergy production less attractive.

Presently, major African producers of bioethanol are Malawi and Swaziland (both from sugarcane) with about 10 mln liters annually each (Maltsoglou et al. 2013). The total production of bioethanol in Africa in 2011 was about 145 mln liters, and the production of biodiesel in Africa is negligible (ibid.).

Ethiopia can serve as a vivid example of the challenges and opportunities faced by African countries in bioenergy development. About 90% of its current energy supply originates from biomass, which is almost exclusively demanded by private households, whereas the industrial and transportation sectors rely on fossil sources-based energy and electricity (REEEP 2012, see Table A-3). Ethiopia plans to generate about 1.8 billion liters of liquid transportation biofuel by 2015 (GTP 2010) in order to increase the blending from the current 10% to 25% (CRGE 2011). The government of Ethiopia has allocated about 23 million ha of suitable land to biofuel development, typically Jatropha caracus, palm oil and castor bean (MoWE 2014). Though the government has targeted large scale jatropha plantation on the so called "marginal lands", the water scarcity remains a key constraint. A key reason for the failure of many large-scale jatropha cultivation projects in Ethiopia was found to be drought stress (Wendimu 2013).

2.2.2 Asia

China, Indonesia, India, Thailand and Malaysia are the main biofuel producing countries in Asia (Tables A-1 and A-2). The bioethanol is produced from maize, wheat, molasses and cassava, while biodiesel is produced mainly from palm oil. Indonesia and Malaysia are dominant in supplying palm oil to the global market, accounting for about 85% of the global palm oil production. The increasing demand for biofuels has contributed to deforestation in Southeast Asia and led to the loss of biodiversity (Fitzherbert et al. 2008).

China has initiated polices aiming for biofuels to account for about 15% of the total transportation fuel use by 2020 (Wang and Tian, 2011). Being the third largest bioethanol producer in the world, China also has the world's biggest household biogas program (Chen et al. 2010).

India is another major player in bioenergy development in Asia. The Indian national biomass policy takes its roots in the 1970s (EBTC 2011). The Indian biofuel program focuses on Jatropha-based biodiesel production and bioethanol production from sugar molasses. However, both are constrained by land and water availability. The Ministry of New and Renewable Energy (MNRE) supports the development of bioenergy initiatives since the early 1990s. Currently, a program on direct combustion and cogeneration of biomass for power generation, and one on deployment of biomass gasifiers for off-grid electrification focus on power supply. The National Biomass program for improved cook stoves targets the inefficient and hazardous use of biomass for cooking. The National Biofuel policy of India (announced in 2009) sets the biofuel blending target of 20% from 2017 onwards (Raju et al. 2012). Moreover, bioenergy has also been given high importance in the Strategic Plan of the Ministry of New and Renewable Energy (2011-2017) (Khanna et al. 2012).

2.2.3 Latin America

Brazil and Argentina are leading exporters of bioethanol and biodiesel, respectively, and thus play key roles in the global bioenergy market. The Brazilian sugarcane-based bioethanol exports have proven to be cost competitive in import-protected US and EU markets as well (Lamers et al. 2011). Hira and de Oliveira (2009) indicate that over 80% of vehicles in Brazil operate on blends with bioethanol, which has resulted in the substitution of over 20% of petroleum use in vehicles.

Brazil is the world’s largest sugar cane producer and bioethanol exporter, maintaining that role since the 1970s (NREL, 2013). Although bioethanol production in Brazil was historically focused on beverages and sugars, within the last 10 years supply has shifted toward fuels (Junginger et al. 2008). Argentina is engaged in biodiesel production and export. Argentina has promoted domestic production and consumption of biodiesel as well as its exports, primarily to the EU (Lamers et al. 2011). The country has promoted biodiesel exports by implementing policies such as tax credits for producers and lower export taxes as compared to other vegetable oil exports. Other significant biofuel producers in Latin America are Colombia, Peru and Paraguay.

2.2.4 Drivers of Modern Bioenergy Development

Many countries are considering modern bioenergy development as an important tool for the reduction of carbon emissions and increasing the security of energy supply, while simultaneously offering opportunities for income generation and development (COM 2005, GBP 2008, Guta 2012). For instance, even in the industrialized European Union, bioeconomy, including bioenergy, already generates about 2 trln Euros (17% of the GDP) and employs about 21.5 million people (Kircher 2012). In agrarian developing countries, bioenergy may offer significant and potentially inclusive growth opportunities (Maltsoglou and Kwaja 2010). For these reasons, several countries have adopted ambitious bioenergy expansion plans (GBP 2008, REN21 2011, summarized in Table A-4).

The drivers of modern bioenergy are complex and inter-related (von Braun 2007, Cushion et al. 2010, von Braun 2013), and can be classified into six categories: environmental, economic, policy-related, social, institutional and technical (see Table A-5 for a non-exhaustive overview of major drivers).

A major driver of modern bioenergy development is its attractiveness to substitute, at least to some extent, the fossil fuels (Parikka 2004, Sathre and Gustavsson 2011), even if full substitution seems currently unfeasible (Sterner 2009). Bioenergy development is also expected to generate new jobs and contribute to rural development, especially in lower income countries (Berndes and Hansson 2007, Hillring 2002, Wicke et al. 2011). Increasing demands for energy are other drivers of bioenergy development. Expected returns from bioenergy may serve as a motivation for the private sector investments, especially in the mature markets. In many cases, such private initiatives are triggered by government subsidies, tax credits and regulatory mandates (Baumol and Oates 1988).

Social preferences for environmentally friendly and sustainable energy sources in the developed countries have been one of the major initial drivers of modern bioenergy (biofuels) development. The perceived environmental friendliness of bioenergy in public discourse and policy making continues to be a powerful driver. The exact nature and magnitude of contributions of bioenergy to these objectives have been questioned though.[1] These drivers also interact closely with another set of institutional drivers, including "green" social mobilization, global coalitions of civil society networks, dissemination by development projects and extension services, as well as organizational innovations in the bioenergy value webs.

Advancement in bioscience and technological innovations may drive the development of the bioenergy sector in numerous ways. Firstly, higher yields and stress-tolerant crop varieties increase land and water use efficiencies and improve food availability. Secondly, technologies for conversion of biomass waste and residue to energy increase use efficiency and productivity, and reduce pollution that arises, for instance, from open dumping of municipal waste. Moreover, innovations create economic opportunities for enhanced use of byproducts, residues and wastes as feedstock, reducing pressure on food security.

However, despite these drivers, in many developing countries, the development of modern bioenergy is often constrained by numerous factors such as: low access costs of fuel wood, technical and market constraints, shortage of skilled labor, lack of transportation and infrastructural facilities, higher costs of modern fuels, prevalence of non-cash economy in rural areas, irregularity of rural incomes versus regular payments for modern commercial energy goods and services, social perceptions and acceptance issues, inadequate legal frameworks or political instabilities (Costello and Finnell 2008, Peidong et al. 2009, Adams et al. 2011, von Maltitz and Staffor 2011, Kowsari and Zerriffi 2011). Moreover, uncertain returns from cultivating energy crops in many developing countries may discourage farmers from investing into bioenergy development (Sherrington et al. 2008).

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[1] See further discussion on this in the section on "Bioenergy and Environment".

3 State of the art: Bioenergy in the Nexus

3.1 Bioenergy in the Water-Energy-Food Security Nexus

The energy sector is becoming more water-intensive as bioenergy and hydropower diversify energy mixes. On the other hand, energy is essential to use water (lifting, pumping, desalination, sewage treatment); and food production is increasingly both water- and energy-intensive. Because of the Water-Energy-Food Security Nexus[2], agricultural, water, energy, industrial and climate policies influence each other and jointly determine outcomes for the poor and the environment, creating complex tradeoffs and potential synergies (Ringler et al. 2013).

On the tradeoff side, crop-based bioenergy and food production compete for land (Rathman et al. 2010, Harvey and Pilgrim 2011). Ciaian et al. (2011) find that high energy prices and bioenergy production have significantly contributed to direct and indirect global land use change, especially in South America, together leading to about 1% annual increase in global agricultural area, often through deforestation. Bioenergy and food production also compete for water (Picket et al. 2008, de Fraiture et al. 2008, Bogardi et al. 2012), which is demanded for feedstock production, pre-treatment, fermentation, gasification or combustion processes and cooling (Berndes 2002, Dominguez-Faus et al. 2009). The tradeoff may cause conflicts, particularly when large scale bioenergy competes with local water demand for food crop production in water-scarce areas (Berndes 2002). Demand for energy may contribute to deforestation, leading to soil erosion (Bazilian et al. 2011), reducing crop productivity and, somewhat ironically, also reducing hydro-energy production through increased silting of dams (Nkonya et al. 2014).

In contrast, there are also numerous possibilities for synergies. For example, water operators spend about 70% of their revenue on energy costs. Mini-hydropower stations have been shown to reduce these energy costs for pumping stations by almost 80% (Kitio 2013); the provision of cheaper micro-scale hydropower, can help in adoption of modern bioenergy technologies (Heltberg 2004), and could potentially lower the demand for less sustainable traditional bioenergy use. Modern bioenergy could allow for increased use of animal dung as fertilizer, instead of as cooking fuel (ibid.), improving soil fertility and contributing to food security.

In the following sections, we review in more detail the current knowledge on the risks and opportunities offered by modern bioenergy development for food security, poverty reduction, environmental sustainability, gender and health issues, technological, institutional and policy innovations, with an emphasis on the impacts at the household and community levels in developing countries.

3.2 Bioenergy and Food Security

Large amounts of literature are available on the link between bioenergy development and food security (von Braun and Pachauri 2006, Naylor et al. 2007, von Braun et al. 2008, Ewing and Msangi 2009, among others). The differences in economic efficiency of resource uses in bioenergy and food production mean that resources will be allocated to the activity with a higher return. This results in higher food prices and the change in (shadow) prices of natural resources, such as land and water, with significant economic, social and livelihood implications (von Braun 2007). The poor, who spend a larger share of their income on food, are worst affected (von Braun 2008). Indeed, biofuels are estimated to have contributed from 3% to 75% to the recent global food price spikes in 2008 (Mitchell 2008, Reuters 2008, both cited from Ciaian and Kancs 2013).

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[2] Water-Energy-Food Security Nexus is a conceptual framework that recognizes the interconnection of these three broad sectors and seeks to develop joint solutions that mitigate the tradeoffs and promote synergies among them (Hoff 2011).

Studies have been conducted on bioenergy and food production linkages using partial (Rosegrant et al. 2008, Chen et al. 2011, Steinbuks and Hertel 2012, Bryngelsson and Lindgren 2013) or computable general equilibrium models (Banse et al. 2008, Hertel et al. 2010, Bouët et al. 2010). Bryngelsson and Lindgren (2013) indicate that a large scale introduction of biofuels would significantly raise maize prices. Rosegrant et al. (2008) show that drastic biofuel expansion could increase the number of malnourished pre-school children by 9.6 million. Adverse effects could be especially high in Africa, with 8% reduction in calorie consumption (ibid.).

There are possibilities for increasing agricultural productivity and making land available for energy crop production alongside food production, and bringing marginal lands into production, thus reducing the competition with food and helping to tackle deforestation problems (Rathmann et al. 2010). However, such measures to limit the production of bioenergy crops on marginal lands can, at best, only partially mitigate food price increases, as there would be strong incentives to grow bioenergy crops on more fertile lands, ultimately leading to accelerated deforestation (ibid.).

There are many emerging technologies for generation of bioenergy from non-food biomass, which may mitigate this fuel-food tradeoff. For example, cellulosic matter can substitute sugar or starch crops in second generation biofuels (Rajagopal et al. 2007). Cellulosic biomass can also have higher yields of fuel (135 GJ/ha) than maize kernel (85 GJ/ha) and soybean (18 GJ/ha) (Lynd et al. 2008). However, cellulosic ethanol still remains commercially unviable (IEA 2004, Slade et al. 2009). Moreover, Chen et al. (2011) find that even with these second generation non-food biofuels, achieving the biofuel mandate (without any subsidies) in the US over 2007-2022 would need to rely on maize for 50% of the production, leading to higher maize prices (ibid.). Only tax credits to maize ethanol and cellulosic biofuels could reduce crop prices by 2022 (ibid.)

3.3 Bioenergy and Poverty Reduction

Modern bioenergy development is believed to have a considerable potential to reduce poverty (Kartha and Leach 2001, Ewing and Msangi 2009, Cushion et al. 2010), for instance by creating employment opportunities (Ewing and Msangi 2009, Cushion et al. 2010) which raise incomes and help mitigate possible negative effects of bioenergy development on food security (Ewing and Msangi 2009). In Malawi, for example, the bioenergy supply chain alone employs about 2% of the total workforce (Openshaw 2010). Poor rural communities may especially benefit from local small-scale bioenergy development (Gerber 2008, van Wey 2009, Chakrabarty et al. 2013). Computable general equilibrium modeling of bioenergy development in Ethiopia (Gebreegziabher et al. 2013), Tanzania (Arndt et al. 2012) and Mozambique (Arndt et al. 2008) find poverty reducing effects. These studies, however, also indicate that policies should consider ancillary benefits, promotion of more productive feedstock and development of rural infrastructure. Promotion of out-grower contracting mechanisms for smallholders to produce energy crops is claimed to be especially conducive for increasing their benefits (Arndt et al. 2008).

Unusual as it may sound, another mechanism for poverty reduction through bioenergy development could be through higher food prices, increasing the incomes of net food selling agricultural households (Rathman et al. 2010, Koh and Ghazoul 2008) and also leading to higher land rental values (Hertel et al. 2008). However, as also discussed above, higher food prices would be detrimental to the welfare of landless rural and urban poor, so the net effect on poverty reduction could be negative (Koh and Ghazoul 2008), and should be evaluated on case by case basis (Ewing and Msangi 2009). For example, for Brazil – one of the global leaders in modern bioenergy production and use, Sawyer (2008) cannot find any impact from large-scale bioenergy development on poverty reduction.

3.4 Bioenergy and Environmental Sustainability

Modern bioenergy development is expected to positively contribute to environmental sustainability through helping in “decarbonizing” the energy production (Pacala and Socolow 2004). Sustainability criteria require that modern bioenergy is developed without diminishing the availability of natural resources or triggering adverse environmental externalities. Environmental sustainability is here used to refer to both environmental friendliness of bioenergy use and sustainable use of scarce natural resources. There are two criteria in evaluating the net impact of bioenergy on the carbon balance: (i) the amount of CO_2 absorbed by energy plants through photosynthesis, and (ii) CO_2 emission in the entire life cycle of bioenergy (production, processing and transportation of biomass feedstock, and consumption) (Jaeger and Egelkraut 2011, Antikainen et al. 2007).

The life cycle assessments of bioenergy production do not always point at net positive carbon balances (Fargione et al. 2008, Stehfest et al. 2010, Lange 2011, Sterner and Fritsche 2011), especially when indirect land use changes are taken into account (Koh and Ghazoul 2008)[3]. Biofuel production through converting rainforests, peat lands, savannahs and grasslands to energy crops in Brazil, Southeast Asia and USA was actually found to create a carbon debt by releasing from 17 to 420 times more CO_2 than the reductions achieved by these biofuels (Fargione et al. 2008). Increases in ethanol production in the US were found to have the potential to divert 12.8 mln ha of cropland to maize production, in turn, triggering the extension of cultivated areas in Brazil (2.8 mln ha), China (2.3 mln ha), India (2.3 mln ha) and in the United States themselves (2.2 mln ha), actually doubling the greenhouse gas emissions over the next 30 years compared to without such a biofuel expansion (Searchinger et al. 2008). However, there is no commonly accepted approach to measure the direct and indirect land-use change impacts of biofuel policies (Warner et al. 2013): (i) they are not always directly measurable; (ii) they are not easily isolated from the myriad of other land-use change drivers (Plevin et al. 2010).

Many models are based on aggregate data and emission estimations and do not distinguish the quality of land, which gives rise to uncertainties. While some data on emissions from direct land-use change are available (Fritsche et al. 2010), the order of magnitude of emissions related to indirect land-use change is still subject to intensive research efforts (IEA 2012). Nonetheless, some studies on indirect land-use change related emissions caused by conventional biofuel crops (sugar, starch and oil bearing crops) indicate that GHG emissions can be very high (Edwards et al., 2010; Tyner et al., 2010).

Biofuel-driven agricultural expansion could threaten biodiversity, especially in areas with endemic species richness such as the Atlantic forest, Amazon and Cerrado biomes of Brazil (Britz et al. 2011, Lapola et al. 2010) and Guinean Forests of West Africa (Koh 2007). Fitzherbert et al. (2008) show that the expansion of oil palm in South East Asia leads to fewer species, habitat fragmentation and pollution. In some very specific cases, agricultural production patterns for bioenergy crops was improving local biodiversity through agroforestry, establishment of perennial herbaceous plants and short-rotation woody crops (Semere and Slater 2007).

On the other hand, the production of biofuels from waste biomass and from energy crops cultivated in degraded or abandoned agricultural lands may offer sustainable reductions in GHG emissions (Fargione et al. 2008). Smeets et al. (2007) imply that bioenergy potential on agricultural land not needed for the production of food and feed equal 215–1272 EJ per year, depending on the level of advancement of agricultural technology. The bulk of this potential is found in South America and the Caribbean (47–221 EJ per year) and sub-Saharan Africa (31–317 EJ per year). However, in both the US and EU the scale of the potential contributions of biofuels to decarbonizing energy production is estimated to be only 1.75% and 1.20% reductions in petroleum input use, respectively (Jaeger and Egelkraut 2011).

3.5 Bioenergy and Health

Use of traditional biomass for domestic cooking and heating can have detrimental consequences on human health through indoor air pollution. Rehfuess et al. (2005) estimate that most of the 3.2 bln people using solid fuels for cooking may be exposed to health-threatening levels of indoor smoke. Diseases such as

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[3] Direct land use change is when non-agricultural land is converted to growing biofuel crops, whereas indirect land use change is when biofuel crops push out food and other crops from current agricultural areas, and farmers convert non-agricultural lands to plant with these replaced crops (Koh and Ghazoul 2008).

chronic obstructive lung disease arise from indoor air pollution of incomplete combustion of biomass while cooking or heating, which accounts by some estimates from 2.5 to 4 million premature deaths annually worldwide (see, Lim & Seow, 2012; WHO, 2006), additionally leading to the loss of some 39 million disability-adjusted life years (DALYs) in 2000 (Smith et al. 2004), i.e. about 2.7% of all DALYs (WHO 2002). Women using traditional biomass for cooking were found to be 3.3 times more likely to suffer from chronic bronchitis and emphysema than those who use cleaner alternatives such as electricity or gas (Rehfuess et al. 2006).

Despite the significance of this problem, there has been insufficient research into the impacts of indoor air pollution (Duflo et al. 2008). Improved access to clean bioenergy sources could, thus, have substantial health benefits, which, in turn, positively affect labor productivity and incomes (ibid.). For example, better access to clean energy could facilitate boiling of water before consuming, thus, lowering the risks of water-borne diseases (United Nations Millennium Project 2005, Rehfuess et al. 2006). Improvements in health through reduced indoor air pollution may also allow for reducing medical expenses for poor households, improve school and work attendance (Duflo et al. 2008). The adoption of 150 mln improved cook stoves in India was projected to reduce DALYs by about 15 mln annually, i.e. 10 improved cooking stoves reducing 1 DALY each year (Wilkinson et al. 2009).

3.6 Bioenergy and Gender Empowerment

Bioenergy production and consumption are also related to gender issues. Women and children are traditionally responsible for fuel wood gathering and cooking in many developing countries (Rehfuess et al. 2006; Hosier and Dowd 1987), reducing women's time from engaging in other activities and lowering school enrollment and study time by children, especially girls (e.g, Nankhuni and Findeis 2004, for Malawi; Chakrabarty et al. 2013, for Bangladesh). About 40% of 1.3 mln deaths among women due to chronic obstructive pulmonary diseases are related to indoor air pollution, while the share for men is only 12% (Smith et al. 2004).

Bioenergy development could additionally be beneficial by providing more productive opportunities for female labor. The likelihood of adoption of improved cooking stoves in India was found to increase with the higher opportunity cost of female labor, resulting in the lower exposure of women to indoor smoke-related health hazards (Kanagawa and Nakata 2007). On the other hand, higher female labor opportunity costs, while resulting in shifts away in female labor from fuel wood collection may increasingly shift the entire burden of fuel wood collection on children. Adoption of modern bioenergy technologies may also not automatically translate into higher female labor market participation or better school performance by children unless there are labor market opportunities to absorb women and both parents and children perceive the potential economic returns from education.

Biofuel production and the modern bioenergy sector could themselves provide such job opportunities for women. On the other hand, higher involvement of women in biofuel production was found to exacerbate bioenergy-food tradeoff in Mozambique without changing the overall GDP as the female labor is reallocated from food production to biofuel production (Arndt et al. 2011). Raising agricultural productivity and improving women's education was however found capable of mitigating this tradeoff (ibid.)

3.7 Bioenergy and Technological Innovations

Technical innovation is an ingredient of sustainable bioeconomy and bioenergy development, as it may help to minimize the risks that may arise from tradeoffs between bioenergy and food security through increasing efficiency and efficacy of resource use (Rajagopal et al. 2007).

Technical innovation in bioenergy has already put forward different biofuel generations. While the first generation comprises starch food crops and vegetable oil, the second generation is generated from non-food crops such as ligno-cellulosic biomass, *Jatropha curcas*, and the third generation is based on algae, which have emerged as potentially promising alternative. Ligno-cellulosic biomass feedstock, such as woody biomass, straw, forest residues, etc, cannot be used as nutrition and therefore lowers the impact on food security, but implications for soil health must be considered. The third generation biofuels based on algae are used to generate multiple modern energy alternatives such as electricity, hydrogen, ethanol, syngas and methanol depending on technical conversion pathways chosen. A study states that "micro-algae appear to be the only source of renewable biodiesel that is capable of meeting the global demand for transport fuels" (Demirbas 2010).

The conversion process of biomass to secondary products takes place in bio-refinery plants. While they are already employed by the food industry to produce food and feed ingredients, so far there is no large-scale application of bio-refineries for bioenergy production (IEA Bioenergy, 2013). Key technologies that are required to expand bioenergy production in bio-refineries are fractionation - the process of refining biomass into sugars, fiber, energy and fuel - and product separation. However, both are still not mature enough to be implemented commercially (ibid.). Technology development in developing countries should consider an integrated approach where biomass production potentials and processing alternatives are optimized jointly.

3.8 Bioenergy, Institutional and Organizational Change

Political economy plays a key role in the development of the bioenergy sector. The success of bioenergy in major producing countries such as Brazil is linked to the political institutions promoting biofuel production. However, the political frameworks often do not provide a level playing field for renewable energy supply (see, e.g. Anthoff and Hahn 2010; Lehmann et al. 2012). There are many politically sensitive issues regarding the premise of job creation, reducing the dependence on fossil fuels, climate change mitigation, preserving the ecological integrity and concerns over large scale land acquisitions in developing countries and their impacts on local livelihoods and access to natural resources by the poor and marginalized. National and international political coalitions as well as political commitment to invest on research and development (R&D), innovation and efficient modern use of bioenergy are also crucial in improving its sustainability.

Germany serves as an example for a policy-driven energy transition – Energiewende – initiated in 2010 (Stegen and Seel 2013). One of the targets is to increase the share of renewables in the energy production to 60%, of which bioenergy, whose share has grown strongest in the past 15 years, is expected to become an important source (BMU 2012). In order to trigger investments in renewable energies, above the market minimum prices are mandated for renewable energy sources. The minimum prices (per kWh) differ by source of energy where bioenergy benefits are substantial. In the context of the globally inter-linked energy markets the long term cost-effectiveness to compete internationally needs to be achieved and will be a key factor for the long-term success of the project.

The experiences made so far with the energy transition provide lessons for policies that target the expansion of renewable energies and biomass in particular. For instance, charging final consumers for the higher energy prices, as done in Germany, is likely to be unfeasible in countries with lower per capita income. Furthermore, the extension of the country-wide energy grid in Germany is not only cost-intensive, but also faces opposition by dwellers living close to the new energy lines. This emphasizes the scope for decentralized energy grids where energy can be produced on a much smaller scale. Net economic growth and positive employment effects of the energy transition, even in the short-term, should encourage the take-up of policies that foster investments in biomass (Blazejczak et al. 2011).

Decentralized community-operated mini-grids and household energy systems using locally available energy resources (modern bioenergy, solar, wind and micro-hydropower) can be an important tool for improving the access to energy by off-grid communities and households in developing countries (Chaurey et al. 2004). Moreover, the access to electricity through decentralized mini-grids could facilitate a wider fuel switching to modern bioenergy (Heltberg 2004). In Assam, India, access to electricity was found to increase literacy rates from 63.3% to 74.4% (Kanagawa and Nakata 2007); similarly, in Brazil, rural electrification was found to reduce poverty by 8% and the Gini coefficient of inequality from 0.39 to 0.22 (Pereira et al. 2008).

The economic viability of decentralized energy systems is related, among others, to their reduced transportation costs and transmission losses (Lauri et al. 2014, other references). Moreover, in many contexts, the extension of centralized grids may not be a viable option due to high investment costs and insufficient centralized power generation (Hellpap 2013). Even in developed countries, urban decentralized energy systems can contribute to reducing greenhouse gas emissions (Chmutina et al. 2014). Other potential benefits from decentralized systems may include the opportunities for local economic development (integration of smallholders into supply chains), strengthening of local collective action and empowering of communities (Fritsche et al. 2006), spillover benefits for advancement of agricultural sector such as organic fertilizers and other inputs (Mohammed et al. 2013, Palit et al. 2011, Bazmi et al. 2011, Mangoyana et al. 2011).

4 The Conceptual Framework

The existing literature on bioenergy, and on energy in general, provides an extremely rich conceptual debate. Kowsari and Zerriffi (2011) classify this debate into four categories: 1) *physical-technical-economic models* (PTEM), in which "changes in consumer demand and energy use patterns are determined by changes in technologies, which are mainly driven by the cost of energy relative to consumer income" (ibid., citing Lutzenhiser 1993); 2) *psychology-based approaches* advocating for inclusion of social variables into economic and technical models. For example, psychology-based approaches were instrumental in the emergence of technology adoption theories such as diffusion of innovation (DOI), theory of cognitive dissonance, the theory of planned behavior (Kowsari and Zerriff 2011); 3) *sociological and anthropological models* which emphasize that individuals do not make their decisions on energy in isolation from larger social processes and various peer groups (ibid.); 4) *integrated approaches* seek to combine all the above from an inter-disciplinary point of view (ibid.). In this regard, the application of Water-Energy-Food Security Nexus as the conceptual framework which guides the present research and is presented further below, can be considered to belong under integrated approaches as it seeks to incorporate both inter-disciplinary elements and also connect energy to other economic sectors such as water and food.

Another important dimension of the conceptual debate is on energy transition. In this regard, the concept of "*energy ladder*" has been widely used in the literature to indicate that the variety and sophistication of household energy use grows with household income (Hosier and Dowd 1987). On the other hand, it was also found that quite often many households do not switch away from less sophisticated energy sources with rising incomes, but instead continue using them along with more sophisticated energy sources, i.e. "*energy stacking*" was observed (Masera et al. 1997, Pachauri and Spreng 2003, Heltberg 2004). It was also found that in certain cases it is possible to "nudge" the households upwards along the energy ladder through public action (Heltberg 2004). In fact, this "nudging" could potentially enable developing countries to "leapfrog" to more efficient and cleaner sources of energy through borrowing more advanced technologies (Goldemberg 1998, Marcotullio and Schulz 2007). In practice, also taking into account the insights of the "energy stacking" model, "leapfrogging" would mean the flattening of the environmental Kuznets curve (Figure 1) where the difference in the areas below the solid curve and the dotted curve represents the avoided environmental damage thanks to the adoption of more sustainable energy technologies. However, "leapfrogging" may be challenging. There are also some studies questioning this possibility due to the lack of relevant technical skills and market infrastructure in many developing countries (Murphy 2001).

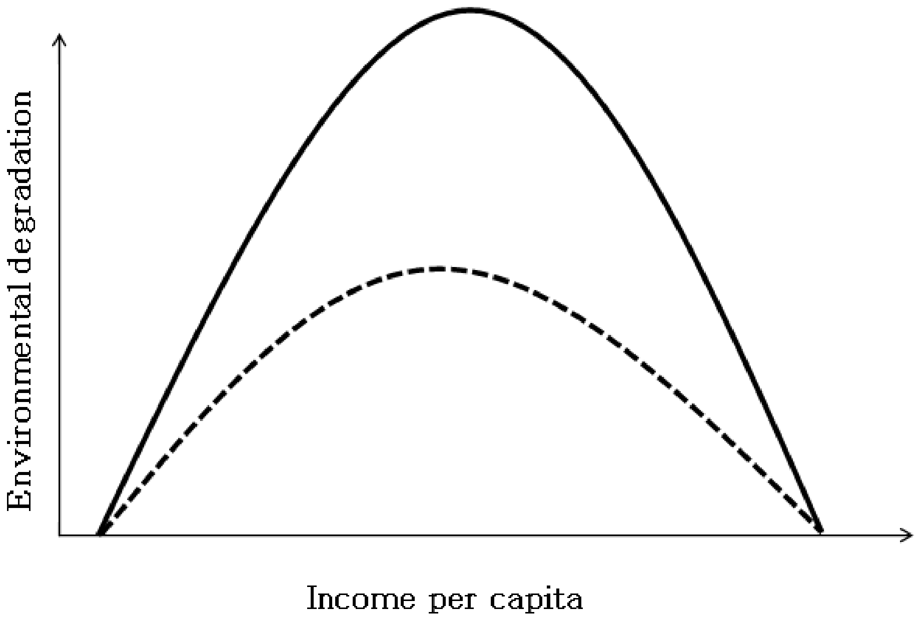

Figure 1. The effect of technological “leapfrogging” on environmental degradation

Source: the authors.
Note: environmental Kuznets curve without (solid line) and with (dotted line) technological leapfrogging

At the same time, “leapfrogging” in energy would also necessitate a “leapfrogging” in institutions to be successful (Han et al. 2008). Figure 1 is two-dimensional and considers only income and environmental degradation. The full picture would involve multidimensional interactions including food security, health and gender issues, employment and labor market changes, institutional transformations, etc.

Building on the Nexus theoretical background and the earlier formulated research objectives and questions, the conceptual framework guiding this research is presented in Figure 2. The elements of the conceptual framework demonstrate the key relationships that need to be studied to advance the proposed research and development agenda.

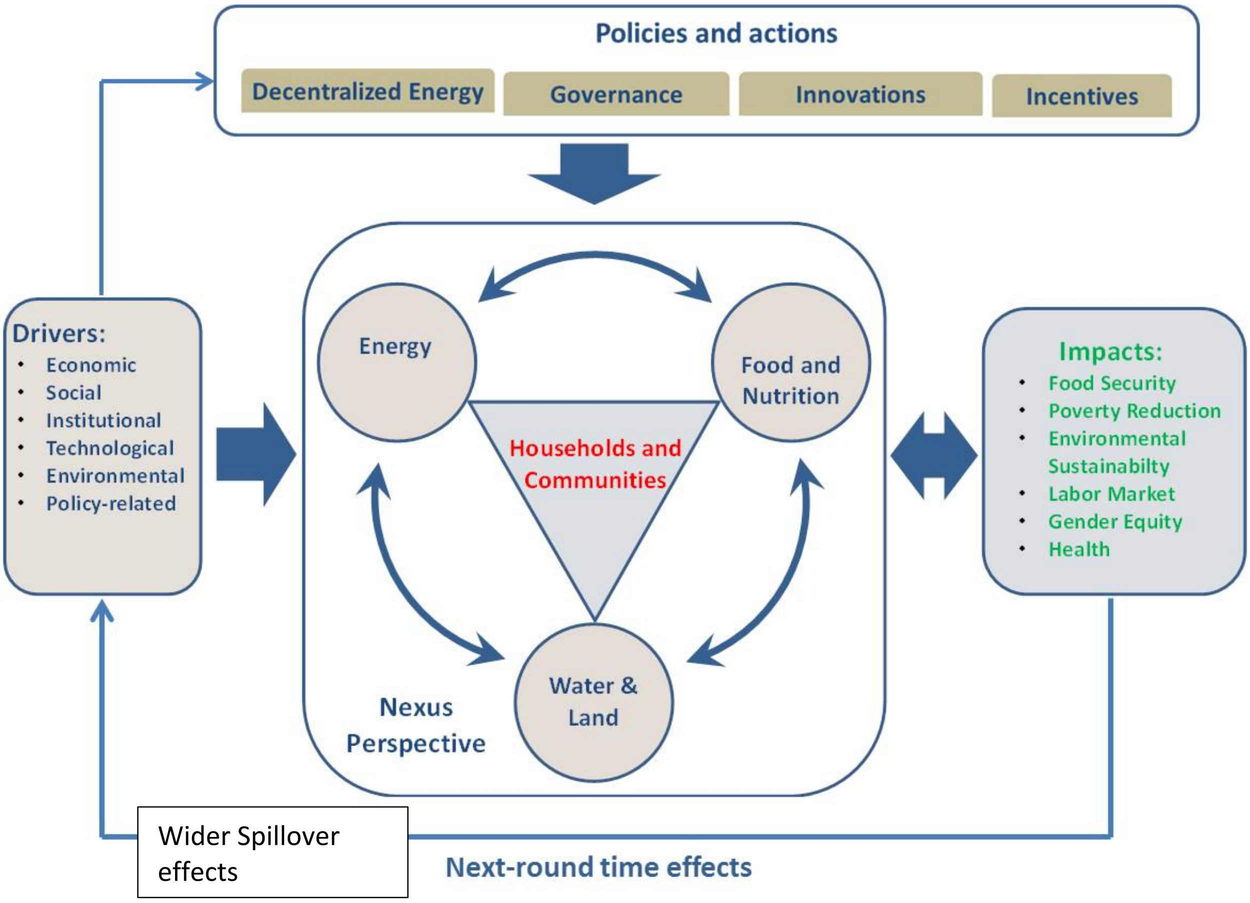

Figure 2. The Conceptual Framework

The economic, environmental, social, policy-related, technological and institutional drivers affect households' and communities' use of natural resources as well as their food and energy production. They are listed in more detail in Table A-5 in the Annex. These drivers act together in complex interactions, resulting in potential tradeoffs and synergies with significant implications on food security, poverty reduction, environmental sustainability, labor market, gender equity and health. There are public policies and various actions by a wide range of stakeholders (described in more detail in Chapter 5) that could intervene in the Nexus linkages to mitigate the tradeoffs and promote the synergies for positive impacts on the listed categories of outcomes. These actions may include such measures as promotion of viable decentralized energy options, better governance and institutions (for example, land tenure security, local participation, promotion of collective action initiatives, improved extension services, etc), innovations (technological and organizational), incentives (subsidies, tax benefits, improved infrastructure, higher market access, etc). The resulting changes in the outcome categories would then modify the nature and relative effects of various drivers. The changes in the drivers would also be modulated by the spillover effects, i.e. to the extent possible, it would be needed to endogenize these spillover effects in the analysis.

5 Major actors in bioenergy development

The effective contribution of modern bioenergy to access and security of energy depends not only on biomass and technology but also on the institutional and organizational arrangements and related actors. For example, market and non-market prices of resources (such as land and water, etc) and ecosystem goods and services are distorted in many countries. Hence, deeper knowledge of stakeholder environment and of the incentives and constraints of key stakeholders is important for accurate analyses of bioenergy development and its impacts.

5.1 Agricultural producers

Bioenergy may benefit both small and large agricultural producers through increased market access, technology, infrastructure, increased demand and prices for biomass and its products and also diversification and intensification of agriculture (Smeets et al. 2007). Around 75% of agriculture production in developing countries is provided by small holder agricultural producers in developing countries. UNEP (2011) argues that greening the small farm sector through promotion and dissemination of sustainable and innovative practices, including modern bioenergy technologies, could be the most effective way to produce more food and reduce poverty. However, the ability of subsistent agricultural producers in adopting new innovative technologies is usually weak due to lack of knowledge and economic assets. Various policies such as farm extension, education and training, awareness-raising and improving access to markets and credit, creating safety nets to absorb likely early-stage failures in the adoption process may play a crucial role in overcoming these constraints.

5.2 The private business

Private businesses are expected to play an important role at all stages of this process as rapid growth in demand for clean energy technologies offers new profit opportunities (Beltramello et al. 2013). Small scale businesses can help tackle the market barriers related to technical, credit, rural infrastructural delivery, biomass logistic and creating markets for feedstock producers, investments in green industry etc.

5.3 Civil society

The development of bioenergy can impact social welfare both positively and negatively. For instance, the advanced value webs may create job opportunities, stimulate economic growth, increase food safety and agricultural productivity, improving quality of life (health, nutrition), thus contributing to improved livelihoods. On the contrary, competition for scarce water and land resources with food production, negative externalities on the hydrology and soil quality, ecological and biodiversity losses may undermine the access of the poor to those resources, thus worsening social welfare.

Despite a general positive attitude towards renewable energies in industrialized countries, the support varies depending on who eventually bears the costs (Wüstenhagen et al. 2007). In this perspective, societal culture and acceptance of the system operation, integration and preferences play a critical role.

5.4 The Government

The role of governments, including local governments, in promoting modern bioenergy production is essential. The bioenergy sector involves a host of policies, regulations and governance issues (Wesseler et al. 2010). But there are risks associated with government failure trying to solve the complex allocative problems in bioenergy which calls for the use of markets and in setting clear incentives and standards

(Purkus et al. 2012). At the same time, government action is needed to overcome market failures. Accordingly, implementing the innovative bioenergy policies requires a proactive government action and societal support and involvement of regional or local governments and municipalities at all levels (Beltramello et al. 2013). Government policies on bioenergy need to be consistent to provide the private sector with more predictable planning horizons (White et al. 2013). The new institutional economics (NIE) framework can make an important contribution to the development of realistic, “second-best” solutions to the allocative problems in bioenergy development (Purkus et al. 2012), taking into account not only the market failures, but also the risks associated with the failure of the governance structures.

5.5 Policies for Bioenergy Production

In order to simulate bioenergy production, governments are using different financial and fiscal incentives which need more careful economic assessment (Peters and Thielmann 2008, White et al. 2013). For instance, BEFSCI (2012) identified the following major incentives:

Transfers/Subsidies: Direct or indirect monetary support to farmers or other actors involved in biofuel production which serve as a safety net, for example Minimum support price program for Jatropha cultivators in India (Kumar et al. 2012, Raju et al. 2012).

Tax credits/ Fiscal Incentives: For instance, under Brazil’s Social Fuel Seals, biodiesel producers are given tax credits (BEFSCI 2012).

Grants: This is generally used to promote good practices in bioenergy production, foster research and development and encourage deployment of renewable technologies, for example, the US program of Sustainable Agriculture Research and Education (SARE) program.

Soft Loans: This instrument is used by several governments to promote biofuels, for example, the soft loan program of Thai government to incentivize rural farmers to start growing energy crops (APEC).

5.6 Coalitions, private-public partnerships, and development cooperation

The bioenergy value web involves multiple stakeholders. Sustainable bioenergy policy should consider the linkages, the objectives of these diverse actors, the incentives needed and ways of bringing them together for solving problems. Private-public-partnerships (PPPs) are critical in implementing incentives for innovative technologies. Political coalitions are needed for assuring sustainability of bioenergy, tackling the negative food security effects and assimilating technological innovations into the value webs. In this sense, in addition to international policies, there are different areas for policy interventions by local governments and for international cooperation. These include tackling capital constraints, barriers to entry, exit and growth, issues of intellectual property rights, skills; correcting market failures and creating conducive value webs, and demand management, entrepreneurship policies, and R&D and innovation policies, technological transfer, promoting S&T, regulating the global bioenergy trade, removing distortionary market policies, etc.

6 Conclusions

Modern bioenergy can offer multiple opportunities for sustainable development. However, bioenergy has complex linkages with food security, land and water use, and other economic activities of households. These linkages may result in complex tradeoffs and negative, including environmental, externalities. On the other hand, they may also offer opportunities for positive synergies.

Studying bioenergy development in a Water-Energy-Food Security Nexus framework can thus help us better understand its real opportunities and potential constraints. The present paper proposes such a Nexus-based analytical framework. This trans-disciplinary framework is considered to be more appropriate for analyzing jointly the multi-dimensional aspects of bioenergy, their inter-linkages and feedback mechanisms with other economic activities of households and communities, rather than looking into bioenergy development in isolation. Bioenergy development needs to be assessed from a systems perspective, including the broader energy system, the food and agriculture system, and the water use systems.

This conceptual framework can thus serve as guidance for empirical research to address the knowledge gaps with respect to the role of energy and specifically bioenergy and other renewable energy sources across the Nexus sectors. This involves firstly more extensive quantitative studies of the tradeoffs and synergies of bioenergy production with sustainable land management, water and food security by households and communities. Secondly, more research is also needed on evaluating the drivers and mechanisms of technical and institutional innovations in bioenergy development at household and community levels including institutional changes. Thirdly, the impacts of traditional use of bioenergy on health and labor productivity need to be identified. Moreover, bioenergy development is expected to have gender-differentiated effects which are not yet sufficiently analyzed. Finally, by accounting for the Nexus tradeoffs and synergies, this framework could contribute to developing enabling policies to catalyze modern bioenergy development among households and communities in developing countries.

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Annex 1. Figures and Tables

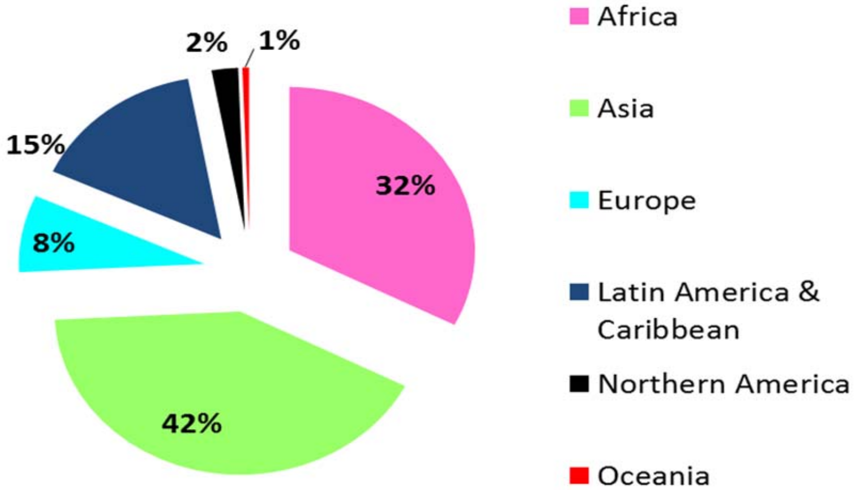

Figure A- 1. The share of continents in fuel wood production in 2009 (in mln m3)

Source: FAOSTAT (2011)

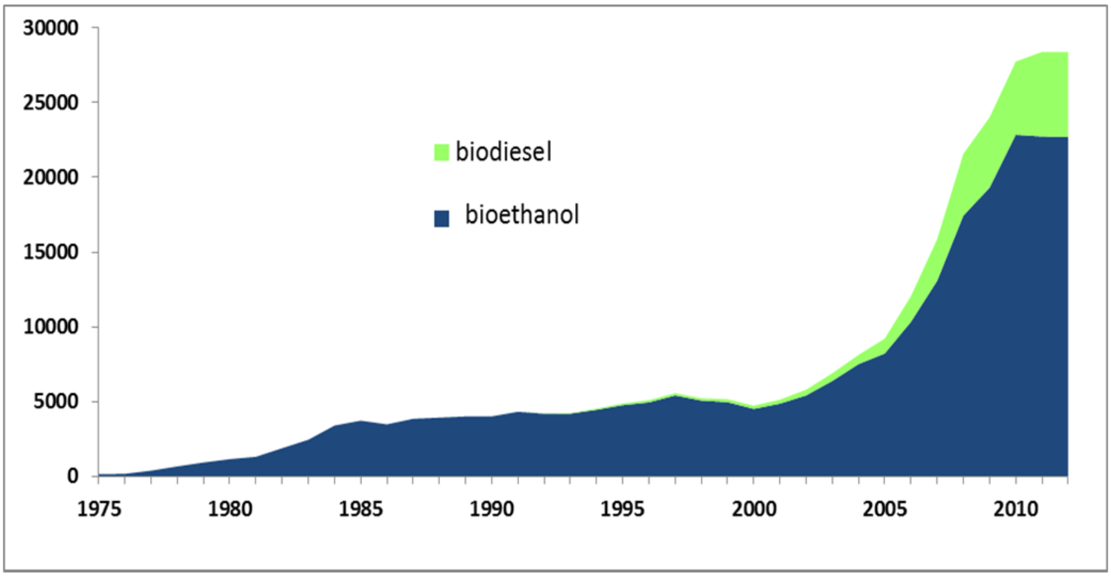

Figure A- 2. Trend in world bioethanol and biodiesel production (in mln gallons per year)

Source: Compiled from EPI (2013)

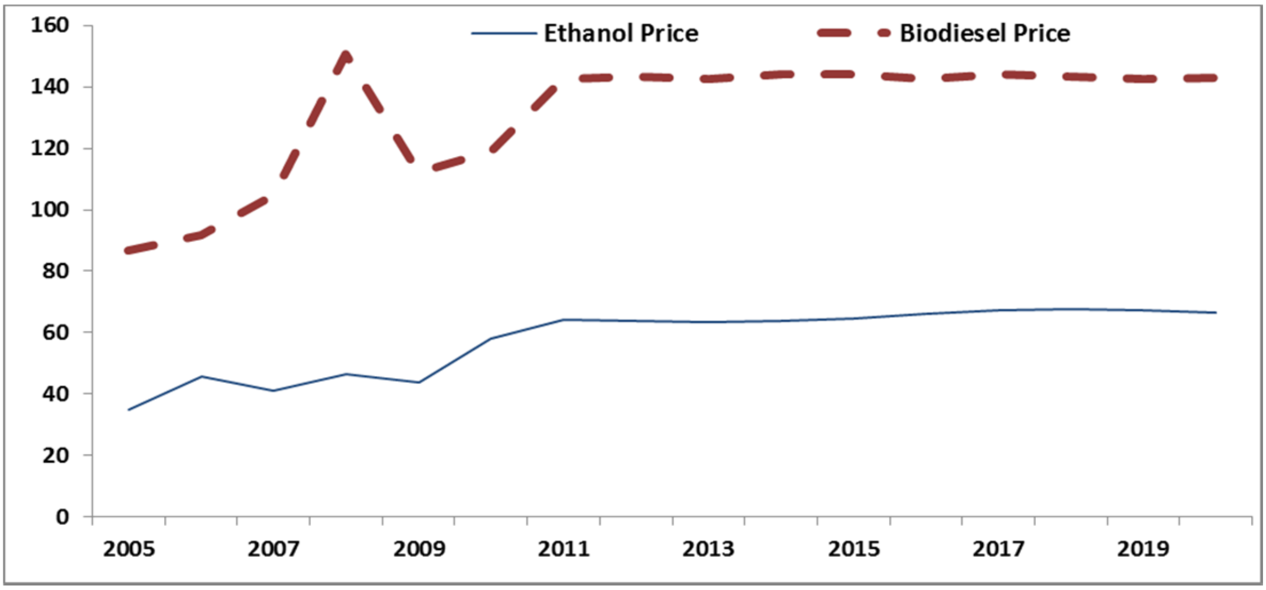

Figure A- 3. The international bioethanol and biodiesel price trends and projections (2005-2020), USD per barrel

Source: OECD-FAO Agricultural Outlook 2011a and OECD-FAO Agricultural Outlook 2011b

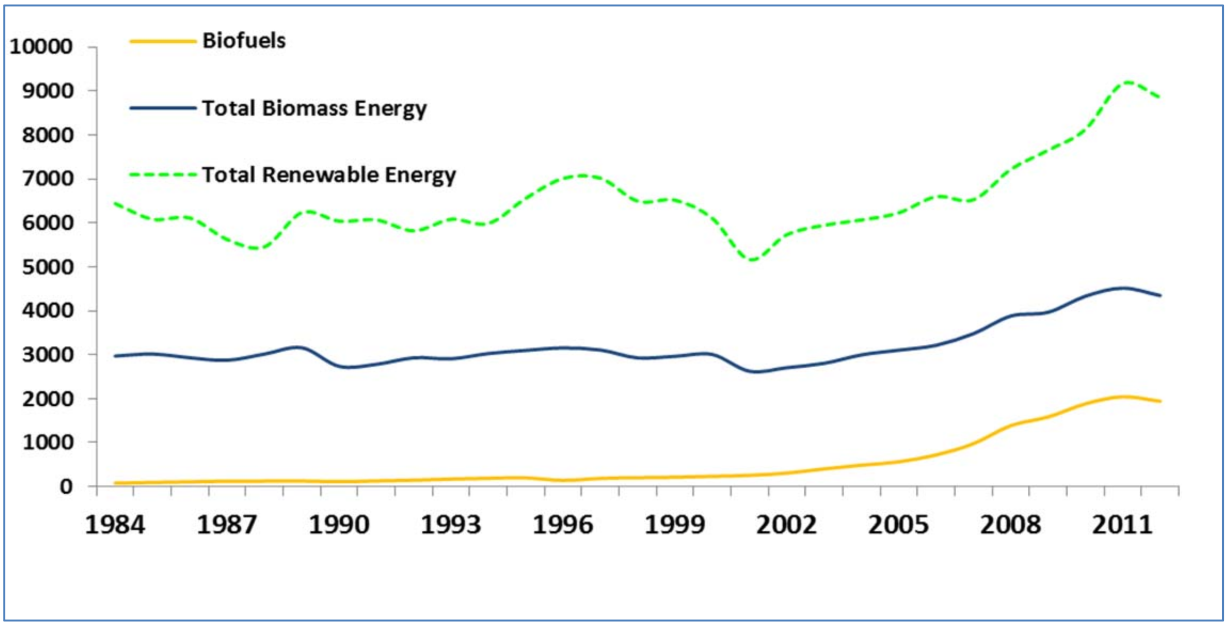

Figure A- 4. The production of biomass energy, biofuels and other renewable energy sources, in billions of British thermal units (btu)

Figure A- 4.
Source: Compiled from EPI (2013)

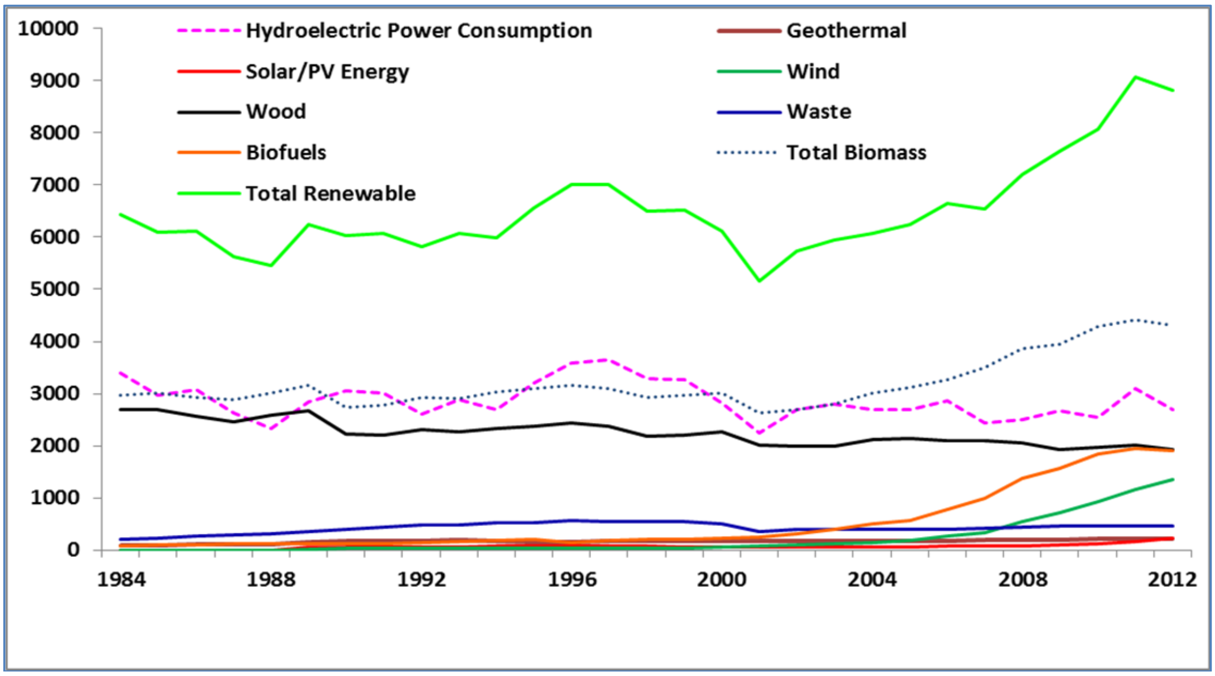

Figure A- 5. World renewable energy consumption in trillion Btu

Source: Compiled from EPI (2013)

Table A-1. Bioethanol production by country in 2011 (in mln gallons)

Country	Production	Share
United States	14,319	63.9 %
Brazil	5,553	24.4 %
China	555	2.4 %
Canada	462	2.0 %
France	301	1.3 %
Germany	203	0.9 %
India	147	0.6 %
Thailand	135	0.6 %
Spain	122	0.5 %
Belgium	106	0.5 %
The rest of the World	839	3.7 %
World Total	22,742	100 %

Source: Compiled from EPI (2013)

Table A-2. Biodiesel production by country in 2011 (in mln gallons)

Country	Production	Share
United States	841	15%
Germany	835	15%
Argentina	729	13%
Brazil	698	12%
France	420	7%
Indonesia	360	6%
Spain	188	3%
Italy	156	3%
Thailand	156	3%
The rest of the World	1,153	22%
World Total	5,651	100%

Source: EPI (2013)

Table A-3. Distribution of Ethiopia's energy consumption in million tons of oil equivalents by end-user, 2009

Sectors	Oil products	Biofuels & waste	Electricity	Total
Industry	0.557	0	0.111	0.668
Transport	1.380	0	0	1.380
Residential	0.310	28.162	0.110	28.582
Commercial & Public Services	0	0.208	0.069	0.277
Total	2.247	28.370	0.290	30.907

Source: IEA (2009)

Table A-4: Bioeconomy Age: new science and policy initiatives, 2009-13

Country	Initiatives
Australia	Bioenergy – Strategic Plan 2012–2015
Brazil	Biotechnology Development Policy (2007)
Denmark	Agreement on Green Growth (2009)
Germany	Nationale Forschungsstrategie BioÖkonomie 2030 (2010)
EU Commission	A Bioeconomy for Europe (2012)
Finland	National Resource Strategy and Sustainable Bioeconomy (2011)
Ireland	Delivering our Green Potential (2012)
Canada	Biorefining Conversions Network (2009)
Malaysia	Bioeconomy Initiative and National Biomass Strategy (2011)
Netherlands	Bio-based Economy 2010–2015
Russia	Bio-industry and Bio-resources – BioTech 2030 (2012)
Sweden	Research and Innovation Strategy for Bio-based Economy (2011)
UK	UK Bioenergy Strategy (2011)
USA	National Bioeconomy Blueprint (2012)

Source: von Braun (2014)

Table A-5. The drivers of modern bioenergy development and their indicators

Dimensions	Drivers	Indicators
Economic	Depletion of fossil fuels Rising incomes, populations and increasing demands for energy Employment generation Green growth and poverty reduction Comparative advantages Profitability of investments Availability of subsidies, tax credits, and regulatory mandates	Share of renewables in the energy mix Number of people employed in the bioenergy sector Share of the bioenergy sector in the economic growth Cost and benefits comparisons with other types of energy Amount of subsidies, tax credits Magnitude of investments into bioenergy
Social	Preferences and tastes, including for "greener" energy Improving human health and safety Empowering women Improving school attendance and performance by children	Lifestyle preferences Health status indicators (incidences of respiratory diseases, DALYs, etc) Impacts on female labor allocation and school attendance and performance
Environmental	Reducing emission from fossil fuel use and mitigating climate change Reducing deforestation Reducing/preventing natural resource degradation	CO_2 and CH_4 concentration in the atmosphere Carbon balance Land use change, life cycle assessment Evaluations of ecosystem services
Policy	Diversifying the energy mix, Energy security Responding to public opinion	Blending mandates, subsidies, tariffs and taxes, Share in transportation fuel Share of bioenergy in energy balance
Institutional	"Green" social mobilization, Global coalitions, Dissemination by development projects and extension services, Organizational innovations in the bioenergy value webs	Technology transfers Public-public partnerships Investments on the value webs
Technical	Technological and Scientific Innovations Information and Knowledge Dissemination	Generation of new bioenergy production technologies Access and search for information on bioenergy technologies

Sources: McKendry (2002), von Braun et al. (2007), von Braun et al. (2014), Tyner and Taheripour (2007), Adams et al. (2011), Martensson and Westerberg (2007), de Fraiteur et al. (2008), Koh and Ghazoul (2008), Peters and Thielmann (2008).

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