GLOBAL LAND OUTLOOK WORKING PAPER

ENERGY AND LAND USE

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United Nations Convention to Combat Desertification

IRENA
International Renewable Energy Agency

CONTENTS

LIST OF ABBREVIATIONS

AEZ	Agro-Ecological Zoning
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CO2	carbon dioxide
CSP	concentrating solar power
eq	equivalent
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GGWSSI	Great Green Wall for the Sahara and the Sahel Initiative
GHG	greenhouse gas
GLO	Global Land Outlook
GMO	genetically modified organism
ILUC	indirect land use change
IRENA	The International Renewable Energy Agency
ISO	International Organization for Standardization
LDN	land degradation neutrality
LUC	land use change
NGO	non-governmental organization
PV	photovoltaic
RE	renewable energy
RED	Renewable Energy Directive
SDG	Sustainable Development Goal(s)
SPaRC	Solar Power as a Remunerative Crop
SRC	short rotation coppice
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
U.S.	United States
W	watt
WF	water footprint

MEASUREMENTS

°C	degree Celsius
EJ	ExaJoule
g	gram
GJ	GigaJoule
ha	hectare
km2	square kilometer
kWhel	kiloWatt-hour of electricity
m2	square meter
Mha	million hectares
MW	MegaWatt
MWel	MegaWatt of electricity
MWh	MegaWatt-hour
TWhel	TeraWatt-hour of electricity
W	Watt

1. INTRODUCTION

This Global Land Outlook working paper is one of a series that aims to synthesize and compile knowledge, focus on the **land-energy nexus** (i.e., taking into account food and water) and provide data, contexts, and recommendations on the interaction between energy and land.[1] The **normative framework** for analysis will be the Sustainable Development Goals (SDGs).

Since the mandate of the United Nations Convention to Combat Desertification (UNCCD) is to combat global desertification and land degradation, the land "footprint" of energy supply and use, referred to in SDG 15, is of particular interest. Currently, approximately 90 percent of global energy demand is met from non-renewable energy (mainly fossil), which leaves its footprint on land through resource extraction (e.g., coal mining), conversion (e.g., refineries, power plants) and their respective infrastructure (e.g., pipelines, fuel storage, transmission lines). Similarly, the development of **renewable** energy, such as biomass, geothermal, hydro, solar and wind, has land consequences, although these differ in scope and form.

This paper identifies and compares the land impact of all terrestrial energy forms. It also focuses on the reduction of greenhouse gas (GHG) emissions from the use and supply of energy, as well as the maintenance and enhancement of terrestrial carbon sinks that are essential to mitigating climate change, as set forth in SDG 13 and the Paris Agreement of 12 December 2015. Meeting these goals will require a rapid scale up of low-carbon, sustainable energy sources and their efficient distribution. Many of these activities have significant implications for land use, management and planning.

1 This report applies the term "land" to represent its area (spatial) dimension, while **functional** aspects of land, such as "soil", are mentioned explicitly.

Energy and land use are further linked to issues addressed by other SDGs, such as those that relate to biodiversity, employment, rural development, soil degradation and water, among others. These linkages are briefly discussed in this publication.

2. ENERGY TECHNOLOGIES AND LAND USE

Historically, humankind has transformed the land for herding and hunting, and cleared its forests and grasslands for agriculture, resource extraction (including fossil fuels), settlements and respective infrastructures (Ellis et al., 2013; FAO and ITPS, 2015). **A key driving force for land use is energy (Smil, 2008).** Fire has been used since prehistoric times to clear the land and prepare food, as well as used for heating and lighting. Today, gaseous, liquid and solid fuels, including electricity and heat, are key commodities in every economic sector, including domestic and commercial buildings, agriculture, industry and transport. Compared to agriculture, forestry, mining (for metals and minerals), and urban settlements, direct land use for capturing energy resources is relatively negligible, at approximately 2 percent of global land.[2]

With growing global energy demand (IEA, 2016), leading towards lower-quality and open-pit (surface) coal mining and gas and oil extraction, using secondary and tertiary recovery technologies (e.g., shale gas and tight oil), the land footprint of non-renewable energy sources will increase over time. In parallel, fossil fuel resources located in fragile environments (e.g., the Arctic) and highly biodiverse remote areas (e.g., rainforests) will be exploited to greater extent (Jones, Pejchar and Kiesecker, 2015; Leach, Brooks and Blyth, 2016). This will increase impacts on land, some of which may be irreversible.

As a direct consequence of the Paris Climate Agreement, which requires global **decarbonization**, renewable energy (RE) sources will continue to expand. Their direct land use effects will become more relevant, and additional infrastructure (e.g., access roads for wind farms, transmission lines for electricity) will require more land than today (Section 2.3.2). To what extent the overall land use balance will be more favorable than for non-renewable sources depends on the mix of renewables, their siting and centralized or decentralized mode of deployment (UNEP, 2016). Innovative deployment of renewables (e.g., solar roof tiles, wind integration with agriculture) can reduce land use pressures, as well as avoid landscape disturbances caused by fossil fuels and nuclear energy (Lovins, 2011).

2 Furthermore, energy prices significantly determine future land use patterns (Steinbuks and Hertel, 2013).

Furthermore, non-renewable energy extraction and conversion require large amounts of water, resulting in an increase in water stress (Section 2.2) that may contribute to land degradation.

The use of fossil fuels is limited by the size of the resource (including future cost and the carbon dioxide (CO_2) budget), while renewable energy is mostly restricted by land use allocation. In addition, the timeframe for land use is of fundamental importance. Renewable energy sources that are managed sustainably are able use the same land for repeated energy extraction (and/or harvesting, in the case of biomass), whereas non-renewable sources require expansion as resources are depleted (Parish et al., 2013; Trainor et al., 2016).

Prior to addressing the quantitative land footprints of energy systems, it is essential to consider the broader sustainability context of energy. The supply and use of energy is closely linked to **almost all** human activities and has implications for the majority of SDGs, as indicated in **Table 1**. Many SDGs are important drivers of land use, and as such, they have the potential to safeguard the sustainable use of land.

Table 1: **Role of Sustainable Development Goals for energy supply/use as drivers for land use and safeguarding the sustainability of land use**

SDG	Key wording	Driver	Safe-guard	Land relevance
1 NO POVERTY	End poverty in all its forms everywhere	(✓)	(✓)	moderate
2 ZERO HUNGER	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**	✓	✓	high
3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being for all at all ages	(✓)	(✓)	low
4 QUALITY EDUCATION	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all			
5 GENDER EQUALITY	Achieve gender equality and empower all women and girls			moderate
6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all	(✓)	(✓)	low
7 AFFORDABLE AND CLEAN ENERGY	**Ensure access to affordable, reliable, sustainable and modern energy for all**	✓	(✓)	high
8 DECENT WORK AND ECONOMIC GROWTH	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	(✓)	(✓)	moderate
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	(✓)		moderate
10 REDUCED INEQUALITIES	Reduce inequality within and among countries			

11 SUSTAINABLE CITIES AND COMMUNITIES	**Make cities and human settlements inclusive, safe, resilient and sustainable**	✓	(✓)	high
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Ensure sustainable consumption and production patterns	✓	(✓)	high
13 CLIMATE ACTION	**Take urgent action to combat climate change and its impacts**	✓	✓	high
14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	(✓)	(✓)	low
15 LIFE ON LAND	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**	✓	✓	high
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels		(✓)	low
17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalise the global partnership for sustainable development	(✓)	(✓)	moderate

Source: Based on United Nations SDG web page at www.un.org/sustainabledevelopment/news/communications-material/

Notes: **Bold text** = SDG directly related to energy, high land relevance; (✓) = partially relevant.

The most relevant drivers and key safeguards identified in Table 1 should be read as follows:

- SDG 1 (end poverty) is not only a partial driver of land use (e.g., through increased investments in RE to foster rural employment and respective income); it also is a partial safeguard for sustainable land use (e.g., by actions to reduce land grabbing).
- SDG 2 (end hunger) will not only increase biomass for food, feed and RE (e.g., irrigation); it also will act as a safeguard to promote sustainable agriculture and improve the integration of renewables into agriculture (e.g., intercropping for biomass).
- SDG 3 (health) has the potential to increase (renewable) energy use and may safeguard respiratory diseases by reducing the health impact from the pollution that is associated with the combustion of fossil fuels and traditional biomass use.
- SDG 6 (water) is a partial driver in terms of wastewater treatment improvement, based on the implication that an increase in the supply of biogas will partially offset land use from other energy sources.
- SDG 7 (sustainable energy for all) - and particularly Target 7.2, "by 2030, increase substantially the share of RE in the global energy mix" – is a key driver to increase the demand for renewables. Since this SDG explicitly calls for sustainable energy, it also can be considered a safeguard.
- SDG 11 (sustainable cities) is a partial driver, based on the implication to sustainable housing (using biomaterials for construction). It is also a potential safeguard if cities require sustainable biomass provision, based on procurement procedures, or in the event that there are more land-efficient city structures.
- SDG 12 (consumption and production) is a driver in terms of increasing the use of biomaterials and potentially safeguarding biomass sourcing.
- SDG 13 (on climate change) is a driver, given that biomass under certain conditions is a low GHG option for energy and materials, and is a safeguard in avoiding high-carbon options (e.g., biomass from conversion of grasslands or deforestation).
- SDG 14 (oceans and marine resources) has the potential to become a partial driver, as well as a partial safeguard, if aquatic biomass is developed for biomaterials and bioenergy supplies (e.g., macro-algae). Furthermore, it may act as a safeguard for offshore wind and ocean/tidal energy development.
- SDG 15 (life on land) has the potential to become a partial driver (restoration of degraded land through biomass cultivation) and a safeguard (biodiversity protection, land degradation reduction).
- SDG 16 (peaceful and inclusive societies) has the potential to become a partial safeguard if institutions are accountable and take into consideration energy sustainability.

- SDG 17 (global partnerships) has the potential to become a driver in terms of the increased use of renewables (especially biomass) and sustainability safeguards (e.g., if the Global Bioenergy Partnership's sustainability indicators for biomass gain further attention).

This brief overview indicates that energy and land are deeply imbedded in the SDGs and will be affected by their implementation, suggesting that their achievement could create opportunities to address, simultaneously, the energy-land nexus by **fostering** sustainable energy **and** sustainable land use. Prior to addressing such options (Section 3 and Section 4), however, the following subsections briefly discuss the **quantitative and qualitative** relationship between energy and land. Many studies and research projects have addressed the land-related impacts on energy systems which, increasingly, are focusing on renewable energy systems.[3] Drawing from this body of knowledge, Table 2 provides a brief synthesis of the land footprint relating to these systems.[4]

Table 2: **Overview of land use intensity relating to a range of energy systems or electricity generation and transport fuels**

			Land use intensity [m²/MWh]				
Product	**Primary energy source**		**U.S. data[a])**	**U.S. data[b])**	**EU data[c])**	**UNEP[d])**	**Typical[e])**
Electricity	Nuclear		0.1	0.1	1.0		0.1
	Natural gas		1.0	0.3	0.1	0.2	0.2
	Coal	Underground	0.6	0.2	0.2		0.2
		Surface ("open-cast")	8.2	0.2	0.4	15.0	5.0
	Renewables	Wind	1.3	1.0	0.7	0.3	1.0
		Geothermal	5.1		2.5	0.3	2.5
		Hydropower (large dams)	16.9	4.1	3.5	3.3	10
		Solar photovoltaic	15.0	0.3	8.7	13.0	10
		Solar – concentrated solar power	19.3		7.8	14.0	15
		Biomass (from crops)	810	13	450		500
Liquid Fuel	Fossil oil		0.6		0.1		0.4
	Biofuels	Corn (maize)	237		220		230
		Sugarcane (from juice)	274		239		250
		Sugarcane (residue)					0.1
		Soybean	296		479		400
		Cellulose, short rotation coppice	565		410		500
		Cellulose, residue			0.10		0.1

Source: Own compilation. Note that data include land use for spacing and from upstream life cycles (e.g., mining).
a) Trainor et al. (2016); b) Fthenakis and Kim (2009); c) IINAS (2017); d) UNEP (2016); e) own estimate for unspecified region (i.e., generic).

3 Note that most of the work concerns the Americas, Australia and Europe, with little coverage of Africa (mostly traditional biomass and biofuel impacts), and Asia (with increasing data being obtained for China and India).

4 Note that Table 2 does not cover heat, given the few studies that exist on this topic. Most of today's renewable heat is produced from combustion of wood, which has a low land footprint if it comes from forest residues or wood industry by-products (e.g., pellets). Solar heat typically comes from rooftop collectors (no land use), and geothermal is highly site-specific.

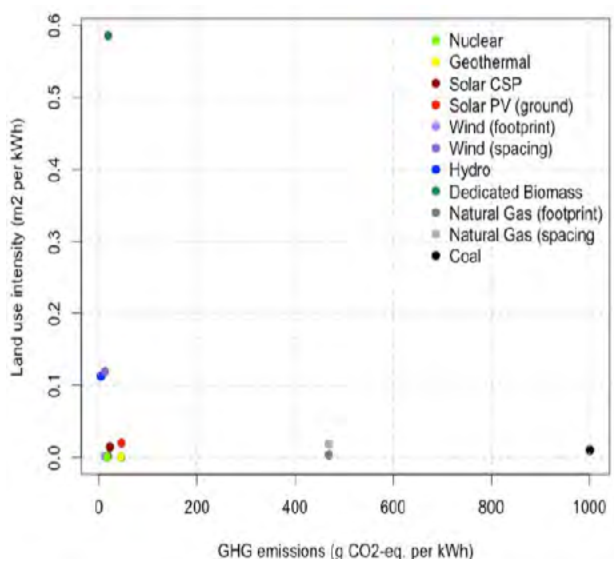
This compilation indicates that the land footprint[5] of energy systems varies between different sources, from 0.1 to 500 square meters (m^2)/Megawatt-hours (MWh) (i.e., by a factor of 5,000). Furthermore, there is variation between energy systems that use the same resource, due to local circumstances (e.g., depth of coal seams, spacing of gas and oil wells, biomass yields, dam height, solar insolation level, wind regime) and options for using co-products, especially for biomass. In general terms, **non**-renewable energy types imply land footprints of 0.1-1 m^2/MWh at the exclusion of open-pit coal mining, while land use from non-biomass renewables is in the order of 1-10 m^2/MWh and 100-1,000 m^2/MWh for biomass (except residues and waste).

These quantitative footprints, however, should be taken into context as follows:[6]

- Land use from **non-renewable** energy has significant soil and water implications that directly disrupt landscapes in addition to the indirect effects from infrastructure, such as pipelines.
- **Non-biomass renewables** typically have small direct footprints, although required spacing suggests a dispersion over large areas (e.g., wind parks) with little soil impediment. Non-intensive direct land use often allows other simultaneous uses, with grazing and even arable cropping possible under or within wind or photovoltaic (PV) farms. While severe, land use from dams is localized as flooding excludes land from other uses (except recreation/fishing) and, for instance, creates barriers to fish migration.
- **Biomass** systems that use dedicated feedstock generate the largest footprints, although depending on the type of biomass, cultivation and harvesting, its ultimate impact on land may be less disruptive or actually positive (Section 3.3). In the case of biomass from **residues and waste**, land footprints are close to zero as they are by-products. A further difference from other energy sources is that other renewable products or materials (i.e., co-products) can be obtained simultaneously **from the same land** when bioenergy or biofuels are produced (Corré et al., 2016). Furthermore, the effects from biomass are not long term, whereas the impact from non-renewable energy production may last for centuries to millennia (Parish et al., 2013).

Tradeoffs (and synergies) exist between land use and GHG emission reduction (Figure 1).

Figure 1: Land use versus greenhouse gas emissions of electricity systems



Source: Fernandez et al. (2016). Note that GHG emissions of biomass do not include possible indirect land use change effects (Box 1).

Section 2.1 discusses energy systems with a **low** GHG tradeoff in more detail. It also considers impacts on biodiversity where necessary.

5 Land use is not only characterized by "occupied area", but also by type of impact (e.g., removal of topsoil versus land sealing); type of land (e.g., pristine natural areas, brownfields, degraded land or forests) and duration and reversibility of "occupation". Land footprints do not capture these aspects, so they are an **indicative metric**.

6 Another way to compare energy use in relation to land is power density (watt (W)/m^2). Solar PV could capture 10-20 percent of incident solar energy, approximately 10-40 W/m^2 for European conditions and when placed on south-facing surfaces. This might be compared with energy systems such as wind (2 W/m^2), again based on conditions common in Europe (MacKay, 2009). The calculation of power density, however, is more location-specific than land use intensity because it is based on the energy that can be instantaneously extracted. Thus, land use intensity is more generalized and comprehensive in a way that various land impacts can be included.

2.1 Brief assessment of emerging RE technologies

RE provided electricity (e.g., communications, cooling, lighting), and modern cooking systems contribute to better health.[7] Bioenergy (Souza et al., 2015) in general, and biofuels in particular (STAP, 2015), improve energy security and rural employment, as well as reduce GHG emissions. Environmental and social impacts of bioenergy and biofuels, however, are quite significant and more site- and context-specific compared to those of other energy sources.

Today, distributed RE systems (e.g., micro-hydropower, solar photovoltaics) are reliable means for rural electrification (UNCTAD, 2014), helping to achieve SDG 7 (Table 1) and the targets of UN Sustainable Energy for All.[8] Due to technological improvements and cost reductions over the last decades - made possible by research and development efforts and policy support - RE is increasingly cost competitive and rapidly expanding, being especially attractive in remote, sparsely inhabited areas where linkages to power grids have not been established and where competing fossil fuels are costly and polluting (ACE, 2016; IRENA, 2015a).

The following subsections discuss relevant emerging RE systems[9] with regard to land impacts.

2.1.1 Bioenergy and biofuels

Bioenergy is the oldest form of RE, with fire from wood being a key tool for survival, sustenance and cultural services since the dawn of civilization. This traditional use of biomass for cooking and heating remains a dominant energy source for more than 2.4 billion people (van Dam, 2017). Today, bioenergy supplies over half of all the renewable energy used worldwide (REN21, 2016). Modern bioenergy for electricity generation (heating with wood chips or pellets, and as liquid fuels or biogas) is increasing and will grow further (IEA, 2016).

Biomass other than from residues has the largest land footprint among energy sources (Table 2) and thus, land-related aspects need particularly critical evaluation when taking into account the use of bioenergy in the future.[10] In 1980, a U.S. study points out that:

> Biomass has the potential to be an energy source that has few significant environmental problems and some important environmental benefits. However, a vigorous expansion of bioenergy may still cause serious environmental damage because of poorly managed feedstock supplies. (OTA, 1980:10-11).

At that time, bioenergy and biofuels were mainly viewed as a means to increase energy security by reducing reliance on oil imports and as a tool for supporting rural development. More recently, especially following ratification of the Paris Climate Agreement and SDG 13, bioenergy is being considered more in terms of reducing GHG emissions and for fostering decarbonization. As FAO has argued, however:

> Some efforts aimed at reducing GHG emissions have led to further intensification of competition for land and water resources. This is the case where countries have moved towards the production of resource-intensive bioenergy instead of choosing other available, and more sustainable, energy sources (FAO, 2017:32).

Bioenergy and biofuel**,** under certain conditions however, **can** significantly contribute to GHG reduction,[11] land rehabilitation (Section 3.3) and infrastructure and sustainable rural development (Best et al., 2008; Souza, 2015; GEF and STAP, 2015), in addition to supporting food security goals (Kline et al., 2017). However, when improperly planned and implemented, rapid large-scale expansion of bioenergy or biofuels could exacerbate emissions from land-use change (Box 1) and pose food security risks (Section 3.1). In that regard:

> Recent work by FAO and other organizations has shown that there are a number of good practices that can accommodate the sustainable production of food, bio-based products and bioenergy, including biofuels. They include agro-ecological zoning and complementing the production of food with bioenergy generation through sustainable agriculture intensification (FAO, 2017:36).

Agroforestry approaches (Section 3.2.1) are being implemented in several regions, particularly Africa and South Asia to grow food crops, side by side, with trees to produce liquid biofuels from oil-bearing nuts and to generate heat and electricity from wood. These approaches are sustainable, accessible and economically viable (Sharma, 2016).

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7 Traditional biomass, using wood, charcoal and agricultural residues for cooking and heating, is inefficient and poses health risks (Lacey et al., 2017). For a discussion of land-related issues, see Section 3.1.

8 See http://www.se4all.org/

9 Geothermal energy is excluded from this paper with the exception of Table 2, due to high site specificity. Marine energy from ocean thermal, tidal range or wave systems (Uihlein, 2016), aquatic and land-based algae (Langholtz et al., 2016; Lauren et al., 2017; Walsh et al., 2016) and non-biomass renewable fuels (Tuller, 2017) are excluded due to early development.

10 Different methods of life cycle allocation result in different land use estimates (Corré et al., 2016). For wood, cascading of different uses improves overall efficiency and reduces land use (Olsson et al., 2016; Thonemann and Schumann, 2017). Note also that aside from land, water use is an important issue for biomass (Box 6).

11 See Creutzig (2016); El Takriti, Pavlenko and Searle (2017); Forsell et al. (2016); IEA Bio (2015); JRC (2015a); Strengers et al. (2016); and Valin et al. (2015).

Aside from solid bioenergy and liquid biofuels, there is increasing interest in **biogas** from the anaerobic digestion of organic residues and waste. This has a high potential for reducing land use and GHG emissions as a substitute for fossil energy. Biogas may well see further global increases when SDGs 2, 6 and 12 are implemented, as these goals may encourage biogas production from manure, sewage water treatment and landfills. Biogas from residues and landfills has particular advantages in terms of land use and climate change.

Furthermore, grass production feedstocks for biogas digesters (Björnsson, Prade and Lanz, 2016) may help to **preserve grassland** that is under threat (Donnison and Fraser, 2016), as well as maintain its biodiversity. The introduction of grasses in rotation with annual crops provides benefits such as improved soil structure, enhanced carbon sequestration, higher soil fertility through nitrogen fixation and suppression of pests and weeds (Tidåker et al., 2014). Suitable grasses can be used as feedstock for biorefineries that provide protein animal feed, along with bioenergy, biomaterials and fertilizers. Grass-derived protein feed can reduce the amount of land required for feed cultivation, thereby mitigating impacts on aquatic ecosystems by reducing nutrient losses from croplands (Bentsen and Møller, 2017).

Box 1: Direct and indirect land use change

The global landscape has seen human-induced land use change (LUC) over millennia - from formerly grass and forest land into settlements, infrastructure, and cropland for food, feed and fiber (Ellis, 2013) - with significant biodiversity, GHG emissions and soil and water implications. LUC is defined as the change from one land use type to another, where land use is generally classified as forest, cropland, grazing land and human settlement.[12]

Direct LUC refers to land use conversion occurring at the site of the crop being studied; in the case of biofuels, it may be deforestation undertaken prior to establishing an energy crop or conversion of cultivated land to an energy plantation.[13] Direct LUC is observable and measurable, for example, by using satellite imagery or spatially explicit databases to detect land clearings and subsequent land use (Gibbs et al., 2010).

Indirect LUC (ILUC) refers to LUC that occurs elsewhere as a flow-on effect if bioenergy crops displace the production of food or feed. As demand for these products remains, production may “move” somewhere else, which can result in deforestation or grassland conversion of other land (and respective GHG emissions). In theory, these ILUC-related emissions, caused by the displacement of biofuel crops, can reduce or even negate their positive effect of replacing fossil fuels. ILUC effects are primarily market-mediated; that is, driven by price effects.

The quantification of ILUC is **possible only by modeling**, which compares a “counterfactual” (baseline) scenario with no bioenergy to a scenario with bioenergy, attributing the differences in LUC to bioenergy. As such modeling is complex - subject to many uncertainties and data variation (especially in the current globalized food market) - the scale of ILUC remains highly contested (IPCC, 2011, 2014).[1] Less uncertainty, however, is associated with strategies to minimize ILUC (Wicke et al., 2012, 2015) in ways such as using feedstock from residues and waste, from sustainable intensification and as feedstock from marginal or degraded land (Section 3.3) - valid options with low negative (adverse) ILUC risks, particularly if biodiversity and social safeguards are in place (GEF and STAP, 2015).

12 These are the categories used by the Intergovernmental Panel on Climate Change (IPCC), which represent a combination of land use and land cover.

13 Note that LUC, per se, is not necessarily negative (Berndes and Fritsche, 2016). For example, integration of energy crops could improve the sustainability of large-scale monocultures of annual crops.

Land-constraining approaches for low-ILUC bioenergy, nevertheless, may prevent optimal land use allocation across larger regions. While bioenergy feedstock can be integrated into food and feed production, expanded biomass production need not be based on the premise that current levels of food production in an area be maintained or increased. Reduced food production in one location can be compensated by increased production elsewhere, without implying deforestation is needed to make room for agriculture.

The implementation of policies to reduce deforestation and the inclusion of all LUC-related GHG emissions in a **global** accounting regime or a cross-sectoral certification system would reduce potential GHG emissions from ILUC to zero. This remains a **long-term** prospect at best.

[1]It is beyond the scope of this paper to fully address the ILUC issue, as the associated literature is extensive (e.g. Delzeit, Klepper and Söder, 2016; De Rosa, Knudsen and Hermansen, 2016; Ecofys 2016a-c; El Takriti et al., 2016; Gerssen-Gondelach et al., 2017; IEA Bio, 2015; Rajagopal 2016; Schebek et al., 2016; Valin et al., 2015; Verstegen, et al., 2016; Wicke et al., 2015).

Biofuel feedstock from **annual** crops (e.g., corn, rapeseed, soybean, sugarcane and wheat) include starch, sugar and oil that might otherwise be consumed as food or feed. This may imply food security risks (Section 3.1) and generally would require significant agrochemical, energy and fertilizer inputs with their associated GHG emissions. Industrial monocultures typically have low biodiversity and carbon stocking values, and cultivating annual crops can negatively impact biodiversity through runoff, spray drift, genetically modified organism (GMO) contamination, and spread of weeds.

Perennial bioenergy crops, such as grasses and short-rotation coppice (SRC), integrated into agricultural landscapes (e.g., agroforestry, intercropping, see Section 3.2), provide biodiversity benefits compared to annual crops, and they help manage degraded land (Section 3.3).

Box 2: Bioenergy with carbon capture and storage

If bioenergy is combined with carbon capture and storage (CCS) (Box 5), it becomes bioenergy with CCS (BECCS), which could result in **negative** GHG emissions, where cultivation of energy crops removes carbon dioxide (CO_2) from the atmosphere. The biomass is then converted to energy (e.g., biofuels, electricity, heat), and the CO_2 released during biomass combustion is captured and stored.

With BECCS**,** bioenergy **would** have a unique advantage over other renewable energy types in terms of GHG reduction if feedstock supply could be managed with low GHG emissions. BECCS is central to virtually every strategy for a world below 2 degrees Celsius, requiring substantive negative carbon emissions by the end of the 21st century (Fujimori et al., 2016; Kartha and Dooley, 2016; UNEP, 2016).

Developing sustainable low-carbon scenarios, nonetheless, requires careful consideration of the land-use implications of deploying large-scale BECCS, as they may implicitly induce large-scale land-use changes that could cancel approximately half of the assumed CO_2 sequestration by BECCS (Kato and Yamagata, 2014) and have significant requirements for water and nutrients (Smith et al., 2016). Furthermore, feasibility and efficiency of large-scale low-GHG biomass supply is questioned (Boysen et al., 2016; Creutzig, 2016; Kartha and Dooley 2016; Muratori, 2016; Vaughan and Gough, 2016) and impacts on biodiversity may arise (Midgley, 2017).

The issues reported for a BECCS pilot plant in China (Pang, 2017) indicate that overall performance remains a challenge, and BECCS may never become a significant and practical reality.

Apart from the technical BECCS, there are **biological** means of sequestering atmospheric carbon (Heck, 2016; Midgley, 2017), e.g., by afforestation and reforestation (Kreidenweis, 2016; Ni, 2016), climate-smart agriculture (FAO, 2016a; Minang, 2015), restoring degraded land (Section 3.3), and biochar (Cowie et al., 2015).

2.1.2 Hydropower

Hydropower is an important RE source, although it inundates land when it involves storing water behind dams, and the changes in the river flow can have impacts on up- and down-stream ecosystems.[14] The direct[15] land use intensity of an individual hydropower system varies from case to case (Table 3).

Table 3: **Overview of area of land flooded after dam construction and land use intensities for examples of individual hydroelectric systems in selected countries**

Name	Country	Annual generation [TWhel]	Inundated area [km²]	Land use intensity [m²/MWhel]
Itaipu	Brazil, Paraguay	91.7	1157	12.6
Three Gorges	China	79.9	853	10.7
Churchill Falls	Canada	30.8	4816	156.4
Cahora Bassa	Mozambique, Zimbabwe	15.8	2048	129.6
Nurek	Tajikistan	11.4	62	5.4
Sysenvatnet	Norway	4.8	11	2.3
Manapouri	New Zealand	3.3	133	40.3
Davis Bor	United States	1.1	99	90.0

Source: based on Scherer and Pfister (2016). TWh_{el} = Terawatt-hour electricity; km^2 = square kilometre; m^2 = square meter; MWh_{el} = Megawatt-hour electricity.

14 Hydropower from dams consumes water due to evaporation from the reservoir surface, potentially contributing to water scarcity, although this can vary significantly depending on the surface and climate (Scherer and Pfister, 2016). Nevertheless, reservoirs provide benefits, such as freshwater storage, flood control and recreation which, in the absence of reservoirs, would require other land.

15 Note that global hydropower development has resulted in the relocation of up to 100 million people due to dam constructions. Resettlement suggests further land use impacts, which are not taken into account in the data given in Table 3. Resettlements also lead to social disruption, especially if indigenous people with traditional social structures are affected, whose livelihoods can rarely be restored (Scherer and Pfister, 2016).

Additional calculations for other dams in Argentina, Brazil and Venezuela give land use intensities of 100-300 m^2/MegaWatt-hour of electricity (MWh_{el}) for generation capacities in the range of 1,000-10,000 MegaWatt of electricity (MW_{el}), with figures of 750-1750 m^2/MWh_{el} for smaller plants (Berndes, 2011). The land footprint of hydropower can cause significant biodiversity impacts (Gracey and Verones, 2016), since destruction of habitats is a key driver of biodiversity loss. Dams can also impact on water quality, obstruct fish migration, and produce some GHG emissions (Box 3).

Many of these impacts are less relevant for run-of-river plants and for mini (< 10 MW) or micro (< 1 MW) hydropower systems that can be better integrated into water flows, do not require large reservoirs and may serve as backbones for rural mini-grids (IRENA, 2016c), thus facilitating the development of RE systems with low land use, such as PV and wind. Furthermore, hydropower can be an important component of future power systems with high shares of variable RE (solar, wind), due to its storage capacity (Section 2.3.1).

Box 3: Methane from hydropower – impact on greenhouse gas emissions

Methane is a greenhouse gas (GHG) with a relatively high global warming potential. For a 20-year time horizon, this potential is 85 times that of carbon dioxide, and around 30 times for a 100 year time horizon (IPCC, 2013).

While GHG emissions from hydropower in northern and temperate regions are typically minor compared to electricity from coal (Hertwich et al., 2016), for example, reservoirs in tropical countries may be a significant source of methane rom anaerobic digestion of submerged vegetation, depending on factors such as biomass inflow from upstream vegetation, inundated biomass type and ambient temperature (Deemer, 2016).

In the case of the Amazon, studies have identified hydropower sites with specific GHG emissions at similar levels to electricity from natural gas (Fearnside, 2016), although the data remains disputed (Sanches-Pereira, Tudeschini and Coelho, 2016).

2.1.3 Solar energy

There are three main options for using solar energy (MIT, 2015):

- solar thermal collectors for water or space heating, typically roof-mounted on individual buildings and thus avoiding any direct land use;
- concentrating solar power systems (CSP) by using mirrors or Fresnel lenses, typically at large scale with generating capacities of 10 to 500 MW, and varying land use impacts depending on specific design and location; and
- solar photovoltaic (PV) systems, which can be very small (e.g., a 50 W panel), although up to more than 100 MW for large-scale utility systems (depending on configuration), with marginal land use from 0 to 1.5 m^2/MWh_{el} (Ong et al., 2013; Hartmann et al., 2016).

Land use for solar systems depends strongly on the level of insolation. The footprint of a given site decreases with higher insolation so that the same system may require up to 1.5 m^2/MWh_{el} for high latitudes, 1 m^2/MWh_{el} for moderately sunny sites and 0.5 m^2/MWh_{el} for sites close to the equator (Lo Piano and Mayumi, 2017; Martín-Chivelet, 2016).

There are numerous strategies for avoiding or minimizing land impacts from solar systems, such as building integration,[16] co-locating solar systems with agriculture and other RE systems (e.g., wind (Ravi et al., 2016), and utilizing degraded land.[17] In the 1980s, research suggested that solar power can co-exist with agricultural production (Goetzberger and Zastrow, 1981), implying little additional land use. The potential of so-called agrivoltaic systems is increasingly recognized (Dinesh and Pearce, 2016) and such systems are being installed in a range of locations (ISE, 2017).

The comparatively small land footprint of solar power fits well with its positive GHG balance (Box 4). In addition, conflicts with water use (e.g., for CSP) and biodiversity (e.g., in arid landscapes and deserts) can be minimized with appropriate land use planning and siting (Section 4). Nevertheless, the system impacts of PV and CSP need to be taken into account, as these fluctuating and variable generation sources suggest infrastructure effects that will influence land use (Section 2.3.2).

16 PV and solar-thermal (hot water) systems can be roof-mounted or integrated into the outer building shell (façade). Furthermore, PV has been integrated into highway noise barriers and, more recently, into the surface layer of streets so that there is no net land take.

17 Niblick and Landis (2016) identified nearly 2 million hectares (Mha) of degraded lands in the United States, which are brownfields, closed landfills and abandoned mines. Solar and wind power on these lands could generate 114 terawatt-hours of electricity without any net land take, representing some 3 percent of current U.S. electricity supply.

Box 4: GHG emissions from photovoltaics and concentrating solar power

Many discussions concern the life cycle of greenhouse gas (GHG) emissions from solar power (i.e., GHG balances including manufacturing of photovoltaic (PV) and concentrating solar power (CSP) systems). These depend largely on the mix of sources used to generate the electricity that powers the manufacturing processes. For silicon-based PV, recent analyses indicates typical values of 30-40 g CO_2eq/ kWh_{el} (Louwen et al., 2016, 2017; Frischknecht, 2015; IINAS, 2017).

For CSP, there is a similar range of GHG emissions from 29 g CO_2eq/kWh_{el} for Chile (with a high share of hydro in the electricity mix) to 37 g CO_2eq/kWh_{el} for South Africa (with a high share of coal electricity), 45 g CO_2eq/kWh_{el} for Mexico and 46 g CO_2eq/kWh_{el} for Spain (Corona, Ruiz and San Miguel, 2016).

Compared to typical GHG emissions (IINAS, 2017) from electricity generated in new coal-fired power plants (around 800 g CO_2eq/kWh_{el}) and in gas-combined-cycle plants (around 400 g CO_2eq/kWh_{el}), solar CSP and PV can achieve 90-95 percent GHG emission reduction. Furthermore, as the dominant source for life-cycle GHG emissions of solar power comes from electricity used in manufacturing the components of solar power devices (e.g., silicon, steel), the GHG emissions of solar electricity are decreasing with growing shares of RE generation.

2.1.4 Wind energy

The land footprint of wind farms[18] varies considerably, based on wind conditions, topography and other factors, although is in the order of 1 m^2/MWh_{el} (Table 2). Thus, wind power, similar to solar, has a comparatively small land footprint and similarly low GHG intensity compared to fossil electricity. Life-cycle GHG emissions (in CO_2eq) from small-scale wind power are up to 50 g/kilowatt-hour of electricity (kWh_{el}), while for large on- and off-shore farms, 10-20 g/kWh_{el} were determined (Dolan and Heath 2015; IINAS, 2017; Kadiyala, Kommalapati and Huque 2016a+b). Large wind farms achieve 95 percent GHG reduction compared to fossil electricity, and less than half of the GHG emissions of PV systems (Box 4).

18 Note that this paper does not cover single turbines used for water pumping or off-grid electricity of farms or rural houses. The direct land use from these installations is typically higher than for larger wind farms, as the rotor diameter is smaller and respective energy yield per turbine is lower. Yet, roof-mounting and less need for road access to deliver large components and cranes for construction may reduce the difference.

2.1.4.1 Onshore wind

Direct land use measures the **area occupied** by wind turbines and other infrastructure, excluding the land between infrastructure elements. This takes into account that overall land use of wind farms does not prevent this land from fulfilling other functions such as agriculture and the provision of other ecosystem services (Denholm, 2009; Hertwich et al., 2015; Ong et al., 2013). Within the wind farm boundaries, approximately 90 percent of the land is **not** occupied by wind power equipment so that this land is available for grazing or cultivation (Ledec, Kennan and Aiello, 2011; McDonald et al., 2009). Wind turbines, nevertheless, can cause noise up to 100 decibels, depending on the type of turbine, power capacity, and wind speed (Kaza and Curtis, 2014). This can restrict land use, especially if human settlements are nearby.

Wind development may also be in conflict with **biodiversity**, since bats, birds and insects can be affected (Gasparatos et al., 2017; Wang and Wang, 2015). Analyses for California found that areas with the highest quality wind resources tend to be those with high biodiversity values (Wu and Williams, 2015). Planning and respective siting can avoid negative biodiversity impacts (Kaza and Curtis, 2014; Kreitler et al., 2015; Obermeyer et al., 2011; World Bank, 2015). Development of land with lower conservation value could lead to lower capacity factors and, hence, increase the specific land footprint, although this also provides opportunity for the co-location of different generation technologies to improve land use efficiency and reduce permitting, leasing and transmission costs.

2.1.4.2 Offshore wind

Expansion of offshore wind development is quite rapid in Europe, with many projects in the Baltic Sea and North Sea. Accordingly, land use and biodiversity impacts have been intensively researched in countries such as Denmark, Germany, Ireland, Sweden, the Netherlands and the United Kingdom, as well as in Europe (EEA, 2009) as a whole in terms of respective guidance for planning (EC, 2011). Key findings are that offshore wind farms have negative impacts on seabirds, although they may be effective in creating refuges for benthic habitats for fish and marine mammals, as has been shown for the North Sea (Hammar, Perry and Gullström, 2016).

2.2 Brief assessment of non-renewable energy technologies

The current dominant global primary energy sources are coal, natural gas and oil – and although the Paris Climate Agreement calls for decarbonization, fossil fuels will have significant shares in the global energy system by 2050 and beyond (IEA, 2016). To reduce the impact of fossil fuels, GHG reduction options are considered relevant (Box 5). The following subsections briefly discuss the land use associated with fossil and nuclear energy.

Box 5: Fossil energy systems with carbon capture and storage

As fossil fuels have a comparatively low direct land use intensity (Table 2) and high greenhouse gas emissions, the combination of coal and natural gas power plants with carbon capture storage (CCS) is considered in many global energy scenarios as an **option** to achieve the 2° Celsius climate target (IPCC, 2014).

So far, little practical experience with CCS exists, although there is significant opposition from many stakeholders. There are many open questions (Arranz, 2015) and critical views are becoming stronger (Ramirez et al., 2014; Williamson, 2016). CCS also has its own life-cycle GHG emissions, which decrease the effective CO_2 reduction (Singh, 2015). Large-scale CCS deployment needs pipelines for CO_2 transport, which implies land use and poses risks (Duncan and Wang, 2014). In a broader sense, seismic risks from CCS (NRC, 2012) also need to be considered, as they restrict land use.

Furthermore, deep underground storage of captured CO_2 may conflict with other subsurface land uses (e.g., groundwater for drinking, fracking for oil and gas development, and drilling for geothermal resources) and are not necessarily compatible with each other (Ferguson, 2013).

2.2.1 Coal

Among fossil fuels, coal is the most polluting and land-intensive electricity technology. Due to timber requirements in coal mines, however, as well as the dumping and extraction at the mining site, underground coal has a higher land footprint (Berrill et al., 2016) than coal from open-pit mines (Ditsele and Awuah-Offei, 2012). Lignite mining is also quite land intensive, as not only excavation must be considered but also the water use and water table impacts that result from accessing lignite seams.

Coal mines have especially large impacts on existing water resources and surrounding land use systems (Wang and Mu, 2014). The impacts are more severe in regions already short of fresh water (Biesheuvel et al., 2016). Post-mining land reclamation is a common practice to restore some of the previous land values in the United States (Skousen and Zipper, 2014), as well as in Europe, India, South Africa - and lately in China (Xiao, Hu and Fu, 2014). Reclaimed mining land, however, often has significantly lower levels of biodiversity and ecosystem services than land that has not been mined.

2.2.2 Gas and oil

On-shore and offshore gas and oil extraction, including fracking, have smaller direct land use footprints per unit of energy supply than coal-based systems. They also have smaller footprints than many RE systems (excluding biomass residues and waste) and rooftop or building-integrated PV (Tables 2 and 4).

Table 4: **Land footprints of oil and gas extraction in various countries**

Land use from extraction of	Land use intensity [m^2/MWh]
Natural gas, China	0.01
Natural gas, Germany	0.15
Natural gas, India	0.02
Natural gas, Netherlands	0.02
Natural gas, Norway	0.03
Natural gas, Russian Federation	0.02
Natural gas, United States	0.13
LNG from Algeria	0.02
Crude oil, Germany	0.02
Crude oil, OPEC	0.02
Crude oil, Russian Federation	0.03
Crude oil, United States	0.01
Oil-heavy from refinery	0.07
Oil-light from refinery	0.15
LPG from refinery	0.11

Source: IINAS (2017). m2 = square meter; MWh = Megawatt-hour; LNG = liquefied natural gas, LPG = liquefied petroleum gas.

In addition, the absolute effects need consideration. For North America alone, approximately 3 Mha of land was devoted to oil and gas development from 2000-2012 (Allred et al., 2015). Land impacts from leaking oil storage and pipelines can be locally severe and infiltrate water bodies, rendering groundwater unusable at larger scales. Building and maintaining the pipeline system to support oil and gas transport can endanger sensitive habitats. Impacts are especially severe when oil spills occur in highly sensitive mangrove areas that are extremely high in carbon stocks (Donato et al., 2011) and play a crucial role in food potential for local populations. In regions with a long history of oil spills, such as the south of Nigeria, continuing dispersion of oil from tidal water movements may have affected large parts of mangrove vegetation (UNEP, 2011).

Land use from fracking has been researched in recent years. Besides potential health and water impacts (USEPA, 2016), cumulative land effects from fragmentation can be relevant for biodiversity (Dannwolf et al., 2014; Ewen et al., 2012).

Due to reservoir depletion, gas and oil extraction increasingly make use of enhanced recovery technologies (e.g., shale gas and tight oil) that increase the land footprint. New gas and oil extraction moves into more remote and fragile environments (e.g., the Arctic), increase the risk of incidents in highly biodiverse areas such as rainforests (Jones, Pejchar and Kiesecker, 2015; Leach, Brooks and Blyth, 2016) and mangroves (UNEP, 2011).

2.2.3 Nuclear

The direct land use from nuclear power plants is very low (Table 2), although the upstream nuclear life cycle (i.e., mining, tailings) can cause local biodiversity impact. Some argue, nevertheless, that nuclear is a favorable option with regard to land use and biodiversity conservation, considering its relatively low life-cycle GHG emissions (Brook and Bradshaw, 2015).[19] Others have been highly critical of this argument and have demonstrated some significant weaknesses and omissions (Henle et al., 2016).

19 Life cycle GHG emissions of nuclear depend mostly on mining technology, enrichment pathway (diffusion versus centrifuge) and plant efficiency, as well as the lifetime of the nuclear plant. As electricity is used along life cycles, the carbon intensity of this background system also has a strong influence. Current GHG emission analyses for nuclear electricity give results in the range of 10-100 g CO_2eq/kWh_{el}, with typical figures of 20-40 g CO_2eq/kWh_{el} (IINAS, 2017; Kadiyala, Kommalapati and Huque, 2016a+b).

Calculated land footprints generally do not include areas affected by nuclear accidents (e.g., Chernobyl, Fukushima) which result in severely restricted land use due to radioactive contamination, lasting up to tens of thousands of years depending on the severity of the accident. Inclusion of just one of these areas roughly doubles the land footprint. If less dangerous radioactive contamination is also included, however, the land footprint increases by an order of magnitude (Andrews, 2011).

2.3 Broader perspective: energy and industrial systems

The previous section discussed the land use effects of energy systems “in isolation”, e.g., based on the individual production of **one unit** of electricity, heat and transport fuel. There are also system effects to be considered, however, especially for electricity[20]; that is, the interaction of energy systems to deliver outputs over time, as well as space.

2.3.1 The interplay of energy technologies on the systems level

Supply of energy typically follows demand, and demand is affected by energy prices that are derived from the costs of generation, transmission and distribution, as well as storage. Thus, there is an **interdependency** of demand and supply, and regional aspects such as climate, structure of economic activity, availability of energy resources and distance between demand centers and supply sources call for different infrastructures.

Furthermore, systems can lock in the impacts of existing equipment, the latter of which often has a long lifetime with related operating costs below the combined capital and operating cost of new equipment. For example, existing coal-fired power plants with high carbon emissions may discourage the installation of new wind or solar plants on power grids, despite the fact that carbon emissions are taxed and – especially - if they are not. Thus, while new renewable power plants are increasingly cost-competitive with new fossil fuel plants, renewable plants may remain locked out once long-lived fossil fuel power plants come online.

The dynamics of renewable energy sources in the electricity sector of many countries demonstrate the transformation of preference for new power plants. The declining cost of many renewable power options is displacing many new investments in fossil fuel or nuclear power generation. Smaller-scale decentralized RE systems are also gaining ground, altering the architecture of transmission and distribution networks.

20 Combined heat and power (CHP) production is also an option requiring a “system view”, as it serves two markets (electricity and heat). For CHP, land use in terms of spatial distribution of heat demand density is a key issue.

At the same time, expansion of variable and seasonal wind and solar resources requires complementary power, such as fossil, hydro or biomass (Section 2.3.2).

In natural gas systems, renewable energy carriers, such as biogenic syngas and biomethane, are slow in uptake. There is substantial unexploited potential to utilize methane from urban waste streams in natural gas networks, for example. Existing pipelines and storage facilities can be used almost without restriction when fossil and biogenic fuels are chemically equivalent, in which case renewable gas has few infrastructure bottlenecks while natural gas networks already exist.[21]

With respect to oil, refineries and storage facilities are able to utilize liquid biofuels through blending or drop-in strategies, so that higher RE shares will not lead to increased land footprints from infrastructure. Furthermore, energy demand sectors (cooling, electronics/lighting, heating, transport) increasingly use electricity, becoming more integrated with decarbonized generation systems, possibly resulting in higher levels of electricity generation.

With regard to the supply (or mobilization) of **biomass resources** for energy, especially from forests, system effects are also relevant. Forest biomass for bioenergy is commonly obtained from forests that are managed for multiple purposes, such as the simultaneous production of pulp, paper and other wood products (Thiffault et al., 2016). Woody bioenergy feedstock mainly consists of byproducts from sawnwood and pulp production, small diameter trees and residues from silvicultural treatments (e.g., thinning, fire prevention, salvage logging) and wood supplies that are economically stranded following the decline of pulp and paper operations (Dale et al., 2017). A large fraction of this biomass is used to supply energy to the forest industry itself. For example, sawmill residues are used to dry sawn wood, and pulp mills use black liquor – a by-product from the pulping process – as an energy source. The electricity and fuels that are produced in the forest industry are also exported to other sectors.

Bioenergy prices are currently far below the level needed to drive shifts in forest management, favouring biomass harvesting for energy over the production of industrial roundwood. The extra income derived from supplying wood for bioenergy can motivate forest owners and forest industries to invest in forest management and technology development. The mobilization of forest bioenergy, however, is not necessarily associated with large additional land claims for wood production. In many places, biomass mobilization for energy will rather be a matter of efficiency improvement and adjustment in the management of existing production forests.

21 For biogas in developing countries, see Section 3.1.

Similarly, the use of agricultural residues and food processing by-flows for bioenergy presents an opportunity to make economic use of materials that were previously considered waste and which required alternative management (IEA Bio, 2016+2017). As described in Section 2.1.1 and Section 3.2, the integration of bioenergy systems into agricultural landscapes offers opportunities to improve resource use efficiency and mitigate pressures on current land use.

As land use and bioenergy production systems diversify and technologies become developed so as to allow biorefineries to produce a diverse mix of food, energy and biomaterial products, it becomes less relevant and increasingly difficult to single out the land footprint associated with specific products. Given these developments, it is essential to evaluate the performance of individual technologies and energy options in the context of aggregated "pathways" of energy and industrial systems as a whole. This would account for system effects and feedbacks, which interact in complex ways, affecting their costs and land use impacts.

The complexities and interdependencies among different energy supply options and technologies also prevent the ranking of options based on simple metrics, such as GHG reduction per hectare or per unit cost. For example, studies that evaluate the climate effects of substituting fossil fuels with biomass in different specific applications often discover that the use of biomass in heat and electricity generation is less costly and provides larger GHG emissions reduction per unit of biomass or land than substituting biomass for gasoline or diesel used for transport.

Integrated modelling studies have identified the use of biofuels for transport as a long-term, cost-effective strategy from a systems point of view, including when decarbonization needs for all energy sectors are explicitly considered (IEA, 2017). The outcome depends critically on how climate policy instruments are implemented and whether options other than biofuels are able to offer far-reaching fossil fuel substitution in the transport sector.[22]

22 While electric vehicles, powered in large part by renewable sources, can in principle take over a large share of freight and passenger road transport, biofuels appear to have a clear advantage for marine transport and aviation, which require high-energy density fuels. To what extent and at what cost non-biomass renewable liquid fuels are able to contribute in the longer term remains an open issue (Footnote 11).

2.3.2 Integration of RE technologies in electricity systems

Increasing shares of RE generation require electricity systems and a corresponding logic that allows for higher shares of variable generation. Renewable electricity from PV, wave and wind, requires frequency and power flow control, storage (which may partially be served by hydropower, Section 2.1.2) and – depending on the spatial distribution of RE supply and load centers - capacity for the transmission and distribution of electricity (Sims et al., 2011). Typically, more infrastructure (e.g., energy storage, transmission capacity) is necessary in systems with higher shares of variable wind and solar systems, leading to greater land use impact than in systems based on natural gas (Berrill et al., 2016).

There are, however, interesting opportunities to align RE expansion with land-sparing infrastructure development. Research for the southwestern United States has identified benefits to co-locating wind and solar CSP plants (Sioshansi and Denholm, 2012; 2013). There also may be transmission benefits from improved capacity factors in combined wind/solar operations, including associated reductions in transmission investments. The potential complementarity of generation patterns should reduce curtailment, grid bottlenecks and transmission grid extensions with generally smaller land footprints.

With a distributed power system, the spatial dimension of these mechanisms becomes increasingly relevant (Rauner, Eichhorn and Thrän, 2016), and options such as biomethane (upgraded biogas) for flexible generation allow higher shares of PV and wind with comparatively low GHG emissions,[23] thus avoiding conflict between land use from bioenergy and GHG reduction from PV and wind. In the longer term, dedicated battery systems and integration with electric vehicle fleets may reduce the need to balance generation.

This clearly shows that the assessment of land use impact from individual RE options may be misleading from a systems perspective. This is the case where integration of comparatively land-intense bioenergy will lead to a lower total land footprint of the energy system by allowing less land-intensive, although variable, RE to play a larger role.

23 Bioenergy enables high shares of variable RE systems by providing balance to the electricity grid and storage options (Arasto et al., 2017).

3. RENEWABLE ENERGY FOR FOOD AND WATER SECURITY

3.1 Bioenergy, land use and food security

3.1.1 Traditional biomass and land use

More than 2.4 billion people – approximately one third of the global population – rely on fuelwood and charcoal (including agricultural residues and animal dung) for cooking, and many businesses use traditional biomass as the main energy carriers for such activities as baking, tea processing and brickmaking (van Dam, 2017). While it is unknown how many trees are cut for these purposes, their impact on land use is highly relevant.[24] Unsustainable wood harvesting and charcoal production, especially in South America, South Asia and Sub-Saharan Africa, contribute to forest degradation and deforestation, as well as to GHG emissions along the charcoal value chain, especially when charcoal is produced using inefficient technologies (van Dam, 2017). Warming climates and increasing population may further exacerbate the challenges of overharvesting and biomass scarcity in these regions.

In Sub-Saharan Africa, charcoal provides 82 percent of urban and 34 percent of rural domestic energy, with consequences such as environmental degradation in drylands, caused by using indigenous trees for charcoal and thus reducing valuable sources of forage (Mganga, Musimba and Nyariki, 2015). Charcoal production is a main driver of forest degradation in the country (Mohammed, Bashir and Mustafa, 2015; Sedano et al., 2016), and fuelwood use causes many problems beyond land, such as health (Lacey et al, 2017) and the time required for its collection, especially for women (Sola et al., 2017). Charcoal produced from sustainably managed forests using improved technologies, however will help mitigate climate change while increasing access to energy and food and providing income-generating opportunities (van Dam, 2017). Several countries now implement such green charcoal strategies (Ackermann et al., 2014), especially in Africa (EFA, 2017; ICRAF and SEI, 2014).

Besides woody biomass, farmers in arid and semi-arid areas often use dried manure for cooking, which reduces soil fertility. In countries such as Ethiopia, this has depleted soil nutrients, reduced food crop yields and increased poverty (Duguma et al., 2014). Policies to subsidize more efficient stoves (GIZ, 2014; Putti et al., 2015) would ensure that more manure remains on the field, thereby improving farm productivity in water-scarce locations (Baumgartner and Cherlet, 2016).

24 Traditional biomass use is much more land intensive than modern bioenergy, due to overharvesting and low end-use efficiency, as it provides only low quality energy services and causes health impacts for women and children (Lacey et al., 2017). Approximately 30 percent of the wood fuel used globally is harvested unsustainably (Bailis et al., 2015).

3.1.2 Traditional biomass and food security

The lack of access to modern energy services in developing countries results in high levels of dependency on traditional biomass. This creates cycles of dependency in which unsustainable land management leads to further degradation, as poor households are unable to finance land improvements to increase their yields of food and fuel crops. The cycle is perpetuated by the expansion of agricultural land through slash-and-burn practices and the extension into wooded areas for charcoal production as a source of off-farm income.

Rural residents in many developing countries are generally more vulnerable to seasonal and climatic changes, while the direct reliance on primary biomass for food and shelter results in low adaptive capacity when compared to their urban counterparts. Consequently, these communities are much less resilient to climate shocks and other stressors, as well as changes in the price of inputs needed at the farm level. One approach that addresses unsustainable land use and adaptive capacity is agroforestry (Section 3.2.1), whereby woody biomass can be sustainably harvested while agricultural yields improve (Mbow et al., 2014a+b). Another linkage to food security arises from biomass scarcity. As biomass becomes scant, one coping mechanism is to cook more efficiently or to select foods that require less cooking time and/or less heat or no cooking at all. Such cases of biomass scarcity tend to lead to lower nutrition for children as the substituted foods are less healthy (Sola et al., 2016).

3.1.3 The "food versus fuel" controversy

The so-called food versus fuel issue has been discussed for quite some time, although the debate among scientists, policymakers and non-governmental organizations (NGO) has intensified following the food and oil price spikes in 2008 (Rosillo-Calle and Johnson, 2010). Food security, according to the definition of the Food and Agriculture Organization of the United Nations (FAO), has four dimensions: availability, accessibility, stability and utilization (FAO, 2008). The relationship between biofuel and food security cannot be understood by relying primarily on price impact or the quantity produced. The other three dimensions are significant, especially with respect to the rural poor who grow their own food and may benefit from higher prices for their crops (Kline et al., 2017).

The discussion on how increased demand for bioenergy affects agricultural systems and food security is not a new topic. It was discussed intensively during the oil crisis of the 1970s and at the start of ethanol programs designed to decrease reliance on oil imports (Brown, 1980; Meekhof, Tyner and Holland, 1980). In 1980, the Office of Technology Assessment of the U.S. Congress raised concerns that:

> using agricultural land for energy crops can compete with feed and food production and thus lead to increased food prices (OTA, 1980, p. x),

and that:

> increased food prices caused by bioenergy production would fall disproportionately on the poor because the purchase of food takes a greater share of their disposable income. Increased food prices also would raise farmland prices, which could increase economic pressures on small farmers and further concentrate ownership of agricultural land (OTA, 1980, p. 13).

Interactions between energy and food systems have continuously been studied since then,[25] and the much-quoted "Feeding Cars, Not People" slogan (Monbiot, 2004), as well as many other publications, brought the issue into broader public discourse (Tomei and Helliwell 2016).

Suddenly, the common wisdom that high levels of food exports from developed countries at **low** prices were an important cause of poverty and food insecurity in developing countries changed course. Today, **high** food prices and lower export levels are considered the **cause** of hunger and poverty (JRC, 2015b). In fact, many NGOs have changed their discourse from "U.S. and EU export dumping of food surpluses that are damaging local food production systems" to "harmful biofuel policies which are depriving the poor of food, land and water".[26]

While food dumping and large-scale use of food crops for bioenergy can impact on local food supplies in developing countries, it is unlikely that both will occur simultaneously. FAO argues that:

> the greater competition between food and non-food uses of biomass has increased the interdependence between food, feed and energy markets. There are risks that this competition may also have harmful impacts on local food security and access to land resources (FAO, 2017:35).

Since the food price crisis of 2007/08, many studies have covered the link between bioenergy (especially biofuels), food prices and food security. Results from this work demonstrate that the effects differ between rural and urban populations, and between net food producer and consumer countries (HLPE, 2013). There is considerable uncertainty around the impact of biofuel demand on agricultural commodity markets and the magnitude of the food price response (Persson, 2015; IFPRI, 2015), mainly due to uncertainties regarding price, elasticity of agricultural commodities and limited empirical evidence.

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25 See, for example, Azar and Berndes (1999); Gielen et al. (2001); McCarl and Schneider (2001); and Sands and Leimbach (2003).
26 Oxfam Briefing Paper 31 (October 2002) and Oxfam Briefing Paper 161 (September 2012), respectively.

Poverty is a key reason for food insecurity, and it depends upon production patterns (i.e., large-scale centralized versus small-scale and outgrower schemes), labour demand and wages, and therefore household income.[27] While there should be care in helping to ensure that the poor and vulnerable are not excluded from the resources they depend on for daily survival, the poverty-reducing effects of bioenergy and biofuel development, especially in developing countries, are relevant to food insecurity and are worthy of further research and implementation activity. Furthermore, issues of crop selection and national price policies must be considered (Koizumi, 2015) alongside land tenure impacts and socioeconomic consequences.[28] Taking these effects into account, analysis indicates that bioenergy and biofuel development can **improve** food security,[29] and that analytical approaches, guidelines and tools will assist in aligning bioenergy policy with food security (IEA and FAO, 2017; Maltsoglou et al., 2015; Kline et al., 2017).

A common response to concerns about food-fuel competition is to refer to the many synergies that exist between food and fuel production.[30] Not least, the use of agricultural and forestry residues as bioenergy feedstock and the application of marginal or degraded lands for bioenergy feedstock production are long-standing strategies to minimize food-bioenergy competition (Hall, Rosillo-Calle and Woods, 1993). A multitude of studies explores approaches that integrate bioenergy into the agricultural and forestry landscapes (Section 3.2) and use marginal lands for bioenergy crops (Section 3.3). Such approaches contribute to food **and** energy security (Kline et al., 2017) and encourage further sustainable management of land and water (Berndes and Fritsche, 2016).

27 See results of FAO's Bioenergy and Food Security studies for Cambodia, Peru, Tanzania and Thailand (FAO, 2010a-f), and more recent work (FAO and OECD, 2011; FAO, 2012; HLPE, 2013; Maltsoglou et al., 2015; Osseweijer et al., 2015; IFPRI, 2015).
28 Note that the issue of land grabbing and related aspects of land tenure, land rights and respective social impacts, while beyond the scope of this paper, are highly relevant. This paper does not address the issue of gender (SDG 5), which is significantly relevant in the overall discussion on agriculture, land and livelihoods.
29 For details, see IFPRI (2015); Lynd et al. (2015); Mirzabaev et al. (2016); Osseweijer et al. (2015); and Sharma et al. (2016)
30 Ironically, opportunities for farmers to produce biofuels from food crops in developing countries are often viewed positively there, in the same way as the use of food crops for biofuels is viewed in the North as contributing to food insecurity. Crops such as cassava are often produced in large surpluses in African countries and might otherwise go to waste, which has led to growing interest in cassava-to-biofuel programs in African countries such as Uganda (Daily Monitor, 2016).

In the case of biofuels derived from agroforestry, tree-borne non-edible oilseeds benefit smallholder farmers if they are planted on the borders of agricultural fields, including those considered marginal and degraded (Bohra et al., 2016). Agroforestry systems are currently used (e.g. in India) to provide local energy to smallholder farmers with co-benefits such as oilcake as fertilizer (Hegde et al., 2016) or for biogas production (Section 3.2.1). The World Agroforestry Centre has applied these technologies to convert five villages in Karnataka, India, into smoke-free villages, leading to an increased interest of neighboring farmers to adopt oilseed-bearing crops. This underlines the importance of peer-to-peer information dissemination, extension services and incentives to facilitate complementarities between different land uses.

In summary, the food security issue is not about trade-offs between food crops and non-edible feedstocks (e.g., lignocellulosic crops such SRC or perennial grasses, agricultural residues and other biogenic wastes); rather, it relates to the **issue of land use complementarity**. In that regard, much of the food versus fuel narrative misses out on the many opportunities to be exploited through climate-smart agricultural approaches (HLPE, 2013; Tomei and Helliwell, 2016).

3.1.4 Joint measures of sustainability: land versus nutrients

In addition to the land use and food issue, the crop-nutrient requirements for bioenergy production are of interest, especially nitrogen. A combined ranking for two criteria was analyzed, with equal weight given to land use and nitrogen use intensity (Table 5).

Table 5: Land use and nitrogen addition intensity for some energy crops used for liquid biofuel production

	Land use intensity		Nitrogen intensity		Combined weighted ranking
	[m^2/GJ]	Rank	[g N/GJ]	Rank	
Sugarcane	23	9	110	2	0.02
Willow	53	5	90	1	0.03
Miscanthus	42	7	210	5	0.03
Sugar beet	19	11	460	8	0.03
Oil palm	30	8	440	8	0.04
Birch	68	2	160	3	0.04
Poplar	72	1	160	3	0.04
Switchgrass	65	3	300	6	0.05
Corn	49	5	490	8	0.05
Sweet sorghum	61	4	390	7	0.05
Grain sorghum	16	13	1000	11	0.13
Rapeseed	16.5	12	1400	12	0.15
Soybean	20	10	3900	13	0.30

Source: Adjusted from Miller (2010). m^2 = square meter; GJ = Gigajoule; g = gram; N = nitrogen.

An obvious conclusion from this comparison is that soybean, rapeseed and grain sorghum are highly inefficient crops for biofuel production compared to almost any other option.[31] Sugarcane scores highest in the initial ranking, and this held true when a sensitivity analysis was conducted for key parameters, such as higher heating value, nitrogen and harvestable yield (Miller, 2010). Lignocellulosic feedstocks, such as woody and grassy perennials, have the highest rankings among non-food crops.

3.1.5 Land for bioenergy: the crucial role of yields

In response to the rising demand for agricultural produce, there is an increasing focus on **sustainable intensification** to improve yields while reducing the environmental impacts.[32] Many examples from around the world indicate that food production in Sub-Saharan Africa and South Asia can be tripled by the widespread adoption of site-specific best management practices resulting from sustainable intensification (Gerssen-Gondelach, 2016; Gerssen-Gondelach et al., 2017; Lal, 2016). In Brazil, there are good prospects for increasing bioethanol and sugar production on existing cane land (Martin et al., 2016), and a more aggregated analysis has shown that there is ample potential for similar bioenergy yield increases (Skeer and Nakada, 2016) that do not compromise sustainability criteria (Rockström et al., 2017). Furthermore, intercropping and better rotation allows for improved yields and crop resilience (Mao et al., 2015), and intercropped biomass could be a low land use intensity option that minimizes competition with food production (Langeveld et al., 2014). Global food demand by 2050 can be met without increasing overall cropland area (Lal, 2016; Rockström et al., 2017), including the use of marginal and degraded land for bioenergy cultivation (Section 3.3). There are many tools and practices now available for improved agricultural land use that integrate bioenergy feedstock production (Herrick et al., 2016).

31 Such crops, however, are considered as biofuel feedstock, where the co-production of biofuels with conventional products results in enhanced productivity, raised agricultural efficiency and resilience.

32 For a discussion of sustainable intensification, see Buckwell et al. (2014); Cook et al. (2015); FAO (2014a+c); Garnett et al. (2013); Garnett and Godfray (2012); Godfray and Garnett (2014); Gadanakis et al. (2015); Loos et al. (2014); Smith et al. (2017).

3.2 Integrating bioenergy into food and water systems

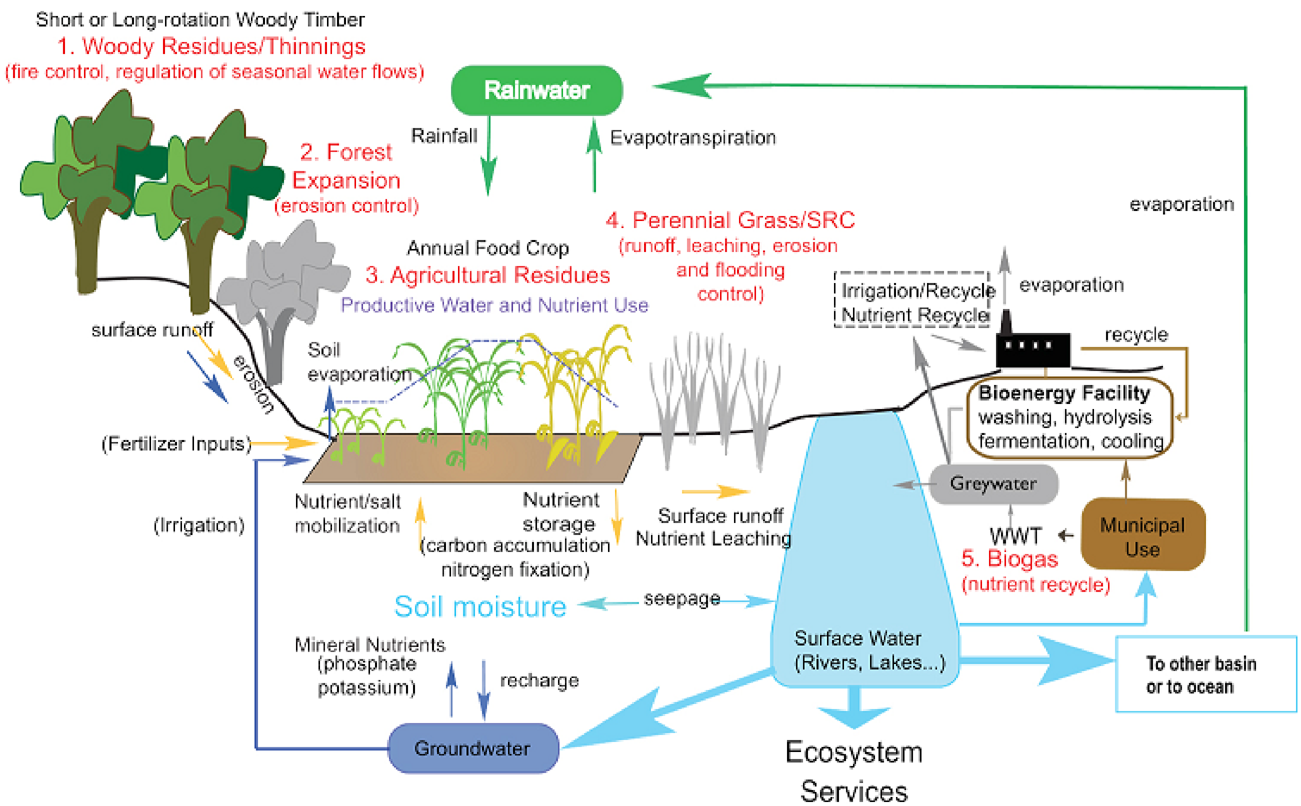
Biomass conversion to biofuel and other products requires substantial volumes of water (Figure 3).[33] Most of this water, however, is returned to rivers and other water bodies and is, therefore, available for further use (Mathioudakis et al., 2017; Rulli et al., 2016). Water use in feedstock supply, though, is different; much of the water is moved from the plant to the atmosphere through evapotranspiration and thus, it is unavailable until it returns as precipitation. Rain-fed feedstock production does not require water extraction from groundwater, lakes or rivers; however, it reduces downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration.

33 There is extensive literature on the water footprint (Box 6) of bioenergy, starting a decade ago (de Fraiture, 2008a+b) with much work following (Berndes, 2008; Gerbens-Leenes, 2008a+b, 2009, 2012; JRC, 2013), and the formulation of the bioenergy-water-nexus (Fingerman et al., 2011; IRENA, 2015b; Otto, Berndes and Fritsche, 2011; UNEP, 2011, 2014).

At the same time, feedstock production may help to increase water infiltration where previous land uses did not. Species (e.g., perennials) that have long crop cycles and large amounts of above- and below-ground biomass are especially effective. Good examples include tree crops and permanent grasslands. Due to the high water demand of certain biofuel crops, it is essential to address challenges from the perspective of water quantity and quality (Bonsch et al., 2016; Cibin et al., 2016; Rulli et al., 2016; Watkins et al., 2015).

Bioenergy systems can provide opportunities to mitigate water pollution impacts, improve water productivity and increase access to water by providing water treatment solutions that simultaneously produce bioenergy and by supplying a wider range of land-use options to optimize the use of land and water (IRENA, 2015b); JRC, 2013; UNEP, 2014). For example, plants, such as willow or giant reed, can be cultivated as vegetation filters, capturing nutrients in runoff from farmlands (Ferrarini et al., 2017; Fortier et al., 2016; Golkowska et al., 2016) and pretreated wastewater from households. Soil-covering plants and vegetation strips can also be located to limit water and wind-driven soil erosion, reduce evaporating surface runoff, trap sediment, enhance infiltration and reduce the risk of soil erosion (Figure 2).

Figure 2: Opportunities for water-bioenergy synergies



Source: Berndes et al. (2015).
Note: WWT = waste water treatment.

Figure 2 illustrates the many opportunities to implement or improve bioenergy production to address the sustainable use of water and soil resources in the long term:

- in lands already under productive forest (1), agricultural (3) or urban use (5), the use of harvest residues may be appropriate; and
- in cases where erosion and water/nutrient flows are excessive, such as sloping land (2) and riparian zones (4), woody and perennial bioenergy crops may provide relief.

As in every land use, inputs such as fertilizers and irrigation should be applied judiciously. The inter-related impact of bioenergy systems on land, soil and water require integrated assessments, taking into account other human activities and ecosystem service requirements (IRENA, 2015b; IEA Bio and GBEP, 2016). With regard to forests and trees outside forests (e.g., in agroforestry and dryland woodlands), recent research has identified interesting links between evapotranspiration, cloud formation and overall cooling (Ellison et al., 2017).

The Global Bioenergy Partnership invited scientists and other experts in 2015 to share results and experiences of how the delivery of food, materials and bioenergy is achieved with good management, as well as the improvement in the state of water. The Activity Group included presentations on a variety of positive bioenergy and water relationships in terms of feedstock and geographical distribution (IEA Bio and GBEP, 2016).[34]

34 For workshop presentations and videos, see www.globalbioenergy.org/programmeofwork/working-group-on-capacity-building-for-sustainable-bioenergy/activity-group-6/pt/

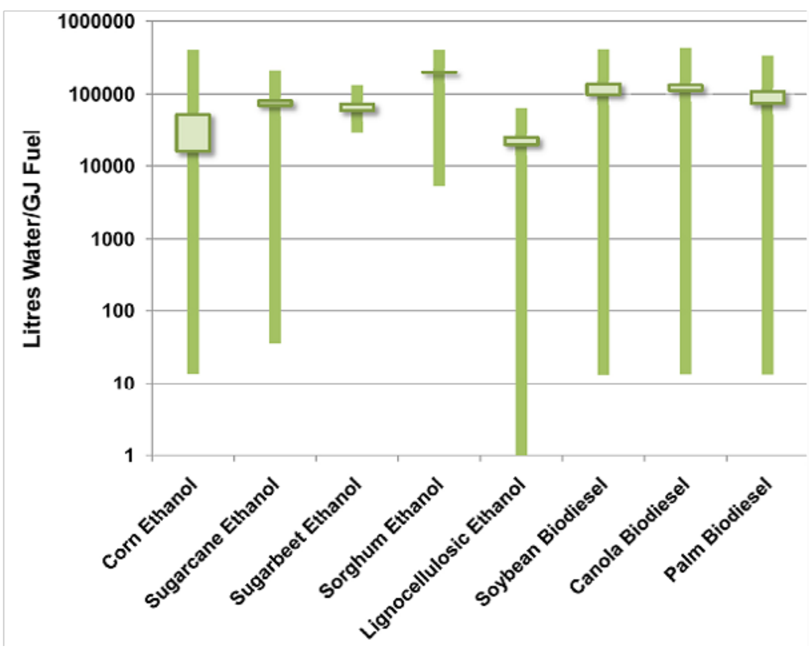
Box 6: The water footprint

Calculating the water used in a product life cycle provides the water footprint (WF) of a product, consisting of three components (Gerbens-Leenes, 2009):

- **Green** WF refers to rainwater that has evaporated during production, mainly during crop growth.
- **Blue** WF refers to surface and groundwater for irrigation, evaporated during crop growth.
- **Grey** WF is the amount of water needed to dilute pollutants discharged during production into the natural water system to the extent that the quality of the ambient water remains above agreed water quality standards. The grey WF is meant as a proxy for water quality impact.

The bioenergy WF varies by order of magnitude (Figure 3). The methodology for quantifying a WF is neither standardized nor validated by measurement. Some methods take into account the scarcity of water in the location of production. Water use is not consistently allocated to multiple products from a particular feedstock. The recently completed water footprint standard by the International Organization for Standardization (ISO) (ISO, 2014) aims to improve consistency in quantifying water footprints. While water footprint estimates are not sufficient to guide decision-making, they must be complemented with other metrics and evaluation frameworks.

Figure 3: Range of water footprints of selected biofuel pathways



Source: Berndes (2015). Solid bars indicate a range of values in the literature, while boxes represent the difference in median and mean values. Lignocellulosic ethanol includes thermochemical and biological pathways.

3.2.1 Agroforestry and land rehabilitation

The integration of woody perennials (e.g., trees, shrubs, palms, bamboo) with food crops and/or livestock is referred to as **agroforestry**. It can contribute to climate change adaptation and mitigation, improve soil, increase yield and income, and thus strengthen food security (Mbow et al., 2014a). Furthermore, agroforestry allows for producing food, feed and several types of bioenergy while being well suited to smallholder plots in developing countries.

Agroforestry also helps rehabilitate degraded and marginal land (Section 3.3), as recent reviews have shown (Borchard et al., 2017; Mehmood et al., 2017). Research in India (Chavan et al., 2015; Dhyani, 2016), Indonesia (Baral and Lee, 2016) and Sub-Saharan Africa (Mbow et al, 2014b; Sharma et al., 2016), for instance, indicates that agroforestry addresses most of the risks posed by conventional biomass crops and thus plays an important role in sustainable bioenergy production.

In Indonesia, farmers practicing agroforestry are less involved in forest clearing and forest product collection than slash-and-burn farmers, indicating that agroforestry can contribute positively to the conservation of local forests (Rahman et al., 2017). India launched its National Agroforestry Policy in 2014 to mainstream tree growing on farms, helping to meet increasing demands for agroforestry products (e.g., timber, food, fuel) and protect the environment (GoI, 2014). Since the adoption of the policy in 2014, grants have been provided to six states, covering approximately 70,000 hectares in agroforestry.[35]

Agroforestry implementation, nevertheless, faces issues of intersectoral planning, outreach to small-scale farmers and guidelines for integration with existing traditional silvo-pastoral community systems (Chavan et al., 2015). Broader adoption of agroforestry is often a matter of an appropriate inclusion of local stakeholders and institutions (Binam, 2017).

3.2.2 Bioenergy as an opportunity to mitigate encroachment

In Sub-Saharan Africa, open rangeland for livestock is increasingly threatened by bush encroachment, which is difficult and costly to control. Here, the use of harvested brushwood for bioenergy can improve land condition while providing energy (EEP, 2017).[36] It has been demonstrated that the cost of restoring land degraded by bush encroachment and woody invasive alien plants in Namibia and South Africa can be substantially offset by using cleared biomass for bioenergy, including fuelwood, charcoal and pellets (Stafford et al., 2017).

35 See https://csa.guide/csa/national-agroforestry-policy-of-india

36 Interestingly, there is also potential for brushwood in Sweden; see Ebenhard et al. (2017).

Much land in South East Asia, especially Indonesia, is invaded by *Imperata,* a perennial grass and common weed in the tropics, resulting in fire susceptibility, soil degradation and compaction, low biodiversity and reduced carbon sequestration. Such grasslands are difficult to reforest or use for agricultural purposes unless labor-intensive land preparation and management practices are employed. Short-rotation forestry (e.g., with fast growing *Acacia* adapted to the humid tropics) and agroforestry can be used to reclaim such land, as these strategies provide shade which diminishes *Imperata* growth and can out-compete the grass, especially on marginal and degraded soils, resulting in significant soil carbon sequestration (Syahrinudin, 2005).

3.3 Marginal and degraded land for bioenergy

Land degradation is an issue of global concern, although there is uncertainty as to its extent. Estimates of total degraded area varies between 1,000 and 6,000 Mha (Gibbs and Salmon, 2015), with a more recent estimate of 2,000 Mha (GEF, 2016). Estimates for marginal land amount to 2,700 Mha by FAO, of which 1,000 Mha is under forest or built-up, with another 222 Mha in use for arable crops (Alexandratos and Bruinsma, 2012). These global estimates indicate an opportunity to fulfill country pledges in connection with the Bonn Challenge to restore 150 Mha of land by 2020, the New York Declaration on Forests to restore an additional 200 Mha of land by 2030 and the AFR100 effort, the last of which falls within the envelope of these initiatives to restore 100 Mha of land in Africa.

Producing bioenergy feedstock on marginal and degraded land (Box 7) contributes to rural and social development (Wicke, 2011) and improves food security in the long term by creating higher productivity land for future use. This, however, will require biodiversity and social safeguards.[37]

37 There is a large variety of work on this, so only a few references are provided (Bringezu et al., 2009; FAO, 2014a; Fritsche, Hünecke and Wiegmann, 2005; Fritsche et al., 2014; German et al., 2016; Hennenberg, Fritsche and Herrera, 2010; Lund et al., 2016; GEF and STAP, 2015; Strapasson, 2015; USDOE, 2017; WBGU, 2009; Wiegmann, Hennenberg and Fritsche, 2008).

Box 7: What is marginal and what is degraded land?

Marginal land is an area not worth cultivating with food crops because of biophysical or economic constraint (e.g., low soil quality, remoteness from markets, water and salinity stress). The term "marginal" is often used interchangeably with other terms, such as abandoned, unproductive, under-utilized, degraded lands or wastelands (Kang, 2013; Hennenberg, Fritsche and Herrera, 2010). The term "degraded" is a relative term for a temporal dynamic; that is, land that has been more fertile or productive in earlier times, now having lost all or some of its capacity for biomass production due to human (e.g., overgrazing, salinization) or natural (e.g., drought, wind erosion) disturbances.

When considering the use of marginal/degraded land for bioenergy production, careful consideration must be given to existing - often traditional - uses by pastoralists and rural communities, as well as potential biodiversity values. Thus, the mere identification of marginal or degraded land by remote sensing (e.g., satellites) does not suffice.

Studies in China have identified a potential of 59 Mha of marginal land[38] suitable for cultivating perennial crops, such as switchgrass and miscanthus (Zhang et al., 2017), representing a bioenergy potential of nearly 20 ExaJoules (EJ) (Li et al., 2017). Approximately 8 Mha of marginal land, mainly in Northeast China and the Loess Plateau, are suitable for miscanthus with a bioenergy potential of more than 1 EJ (Xue et al., 2016). The potential bioenergy from cassava on marginal land under rain-fed conditions in GuangXi Province, Chinam is approximately 2 EJ (Jiang et al., 2015).

Similar analyses were carried out for degraded lands in India, where approximately 14 Mha of marginal and degraded lands have been identified for potential plantation with perennials (Wani, 2012). More recent work suggests 39 Mha of wastelands (Edrisi and Abhilash, 2016) to 46.5 Mha (Patel, Gami and Patel, 2017), corresponding to the findings of India's "Wastelands Atlas" (GoI, 2011). There are regional hotspots in four states (Natarajan et al., 2015+2016), and up to 1 EJ of bioenergy could come from these lands if cultivated with perennials.

Producing bioenergy feedstock on marginal and degraded land contributes to rural, social and economic development by using land with no or little previous productivity (Wicke, 2011) and it improves food security in the long term by increasing land productivity for future use. In these circumstances, biodiversity and social safeguards need to be carefully taken into account.[39]

In Africa, based on the pledges made so far under the AFR100 initiative, a potential of up to 6 EJ has been identified from the planting of SRC on 73 Mha of degraded lands (van Loon, 2017). This is roughly consistent with estimates that 33 EJ of bioenergy may be extracted from degraded land on a sustainable basis if SRC wood or grasses were planted on all 350 Mha pledged for landscape restoration under the Bonn and New York initiatives (IRENA, 2016a).

Degraded lands have also been identified in the United States, for example, with up to 121 Mha (Niblick and Landis, 2016). Extensive planting of switchgrass on these lands could reduce soil erosion in the United States by more than 10 percent (USDA, 2017) and provide a large volume of biomass with positive environmental impact (USDOE, 2017). Analysis of highly saline lands in Spain demonstrates that perennials, such as giant reed, could yield up to 5 (Sanchez, Curt and Fernández, 2017).

Marginal lands may be suitable either to grow SRC or perennial grasses native to these lands, which are better adapted to poor soil. Energy crops grown on marginal lands will not only provide cellulosic biomass without competing with food crops; they will assist in reclaiming those lands and in their mitigation potential without posing food security risks.[40] A recent overview of bioenergy crops suitable for marginal and degraded lands and their respective energy potentials clearly indicates that these present a valid option in many parts of the world (Mehmood et al., 2017).

38 This figure corresponds to the maximum of 58 Mha of degraded land identified for China (Schweers et al., 2011), and is in good accordance with the range of 20-64 Mha identified in a recent analysis that represents 5 percent of the total land area of China as marginal (i.e., 48 Mha) and 17-18 percent of China's land as rest land (Li et al., 2017).

39 See for example FAO 2014b; Fritsche and Iriarte, 2014; German et al, 2016; Thrän and Fritsche, 2016; USDOE, 2017; WBGU, 2009).

40 Perennial biomass crops improve soil carbon stock (Berhongaray, 2017; Chimento, Almagro and Amaducci, 2016; Dhyani, 2016; Ferchaud, Vitte and Mary, 2016; Georgiadis et al., 2017; Harris et al., 2017; Jungers et al., 2017), thus sequestering carbon. It also enhances biodiversity in agricultural landscapes (Carlsson et al., 2017; Haughton et al., 2016; Verheyen et al., 2014) and improves ecosystem services (Blanco-Canqui, 2016).

Perennials on marginal land have been tested successfully,[41] especially *miscanthus* (Barth et al., 2016) in various countries, including China (Liu et al., 2016; Xue et al., 2016), the European Union (EU) (Lewandowski, 2016), Serbia (Djordjevic, Milosevic and Milosevic, 2016) and the United Kingdom (Clifton-Brown et al., 2017). Furthermore, not only grasses (e.g., switchgrass) and SRC (e.g., poplar, willow) but also forbs, such as *Sida hermaphrodita*, are suitable for cultivation on marginal land (Nabel et al., 2016). While soil quality can be improved with SRC or perennial grasses (thus increasing soil organic matter, soil structure and biodiversity), scientific research contributes to the improvement of soil productivity, as it does in Brazil (Langeveld and Quist-Wessel, 2014).

Total global potential energy production on degraded lands, outside of crop, forest or pastoral land, is around 25 EJ (grassy biomass) and 32 EJ (woody biomass), with lightly degraded soils excluded, since these soils are potentially suitable for subsistence production (Nijsen et al., 2012).[42] This agrees with other studies (Pogson, Hastings, Astley and Smith, 2013). The technical potential for bioenergy from salt-affected land is estimated at 56 EJ, and 32 EJ of bioenergy could come from degraded land (i.e., a total of 90 EJ (Wicke, 2011)). The global **economic** potential of bioenergy from salt-affected soil is 21 EJ at a cost of 2 €/GJ, increasing to 53 EJ at a cost of 5 €/GJ (Wicke, 2011).

Besides SRC and perennial grasses, bamboo grows on marginal land in India for biomaterials, with processing residues used for bioenergy (Patel, Gami and Patel, 2017). In Indonesia, intercropping of castor beans has shown great potential to improve agriculture land productivity and biodiversity (Jaya et al., 2014). There is significant potential to harness an alternative form of photosynthesis, crassulacean acid metabolism to produce bioenergy in arid and semi-arid areas. For example, *Opuntia ficus-indica*, *Euphorbia tirucalli*, *agave* and *prickly pear* (a fast-growing cactus native to Mexico) are judged to be potential bioenergy feedstocks (Mason et al., 2015; Davis et al., 2017; Santos et al., 2016).

41 There are also various plants for sustainable **phytoremediation** of contaminated land (Abhilash, 2016; Pandey, 2016), of which especially perennials such as miscanthus, reed canary grass and switchgrass have been analyzed in many countries, as in India (Sinha, 2013), Indonesia (Borchard et al., 2017), Italy (Pulighe et al., 2016), Latvia (Rubezius, Venslauskas and Kidikas, 2016), Poland (Radwanska et al., 2016), Ukraine (Pidlisnyuk et al., 2016), the United Kingdom (Jiang et al., 2015), and the United States (Niblick and Landis, 2016; USDA, 2017).

42 Most of the degraded land with potential for energy crops is located in developing countries. Part of this land may be in use for rural livelihood or pastoral activities. Thus, not all lands should be regarded as idle resources (Nijsen, 2012). Nevertheless, this sort of land may benefit most from bioenergy-driven investments and provide transitional pathways for the farmers who are under pressure to over-use their land, as highlighted above.

Findings from recent research indicate that marginal and degraded land offer a significant potential for sustainable bioenergy production in many parts of the world.[43] Cultivation on poor soil, however, typically leads to low productivity and **higher feedstock costs** compared to cultivation on more fertile soil (GEF and STAP, 2015), with local markets likely to be restrictive. Thus, bioenergy from marginal and degraded land is not only subject to sustainability safeguards but also to regulatory land use restrictions or economic incentives.[44]

3.4 Land-sparing approaches: substantial bioenergy potential

In view of concerns that bioenergy production may compete with food production and lead to GHG emissions from land use change, IRENA (2016) has explored the potential to expand bioenergy production *without competing with food production or causing land use change*, by

- more thorough collection of agricultural residues, as well as freeing of land for bioenergy crops (especially high yielding wood or grass species) through sustainable intensification (higher food crop yields and more efficient livestock husbandry),
- landscape restoration (pursuant to Bonn Initiative and New York Declaration pledges to restore 350 Mha of degraded land), and
- reduction of waste and losses in food chains (which amount to roughly one-third of all food produced for human consumption).

IRENA has found that this could "free" over 2,000 Mha of land (550 Mha from higher crop yields, 950 Mha from more intensive use of pastureland, 270 Mha by reducing food waste).

43 There is extensive ongoing research on biomass from degraded land, for instance in the EU, including INTENSE (intensify production, transform biomass to energy and novel goods and protect soils), Phyto2Energy (phytoremediation-driven energy crop production on heavy metal degraded areas as local energy carrier) and SEEMLA (sustainable exploitation of biomass for bioenergy from marginal lands in Europe). For EU global activities on sustainable land, see EC (2016a).

44 For example, Jatropha is a perennial plant that grows on marginal/ degraded land with low water requirements, promising low-ILUC biofuel. Much Jatropha cultivation, however, has taken place on arable land as, without regulatory restrictions or subsidies, the economic logic of "producing most on best land available" will not deliver on implementing crops on marginal/ degraded land but on more fertile land, with respective implications for food security and GHG emissions.

Assuming yields of 10 t/ha and energy content of 15 GJ/t, some 300 EJ of primary bioenergy could be provided. Converted to 240 EJ of electricity and heat at 80% efficiency, or 120 EJ liquid transport fuel at 40% efficiency, this bioenergy could greatly expand energy access in developing countries or meet a large share of the world's transport fuel needs (IRENA, 2016).

3.5 Non-biomass renewable energy and the food-land-water nexus

Besides bioenergy, other RE sources play a key role in agricultural and food production systems (Box 8). One example relevant for many semi-arid and arid areas of the world is the improved use of scarce water resources by using PV and small wind systems for small-scale irrigation (Rockström et al., 2017). Solar-powered drip irrigation significantly augments household income and enhances food security by conserving water, improving power reliability, and conserves land and space (Burney et al., 2010). The Indian project, Solar Power as a Remunerative Crop (SPaRC), offers farmers a guaranteed buy-back of surplus solar power they produce, provided they are connected to the electricity grid. SPaRC is in pilot operation in the sun-rich state of Gujarat.[45] In addition, the Smart Villages initiative (http://e4sv.org) demonstrates best practices for integrating RE into production landscapes while being economically attractive.

RE systems for rural electrification are not only relevant for residential uses (e.g., lighting); they also benefit food processing (e.g., solar cooling and refrigeration), which can reduce food loss in value chains and, thus, improve land use efficiency. Similarly, RE can play a role in desalinizing water to improve food and water security, as well as generate sustainable energy.[46]

45 See https://csa.guide/csa/solar-power-as-a-remunerative-crop-sparc

46 In the short term, however, the largest impacts of RE on water resources should be expected from displacing water-intensive coal mining, fracking and oil sands production.

Box 8: Energizing agriculture

Expanding access to clean energy in low-income countries is a key component of global development efforts to address energy poverty and food insecurity, and it contributes to achieving several of the SDGs (Table 1). Nevertheless, there are significant barriers that hinder the integration of clean energy technology in agriculture development. Powering Agriculture (https://poweringag.org) is a joint initiative of donors and private enterprises that utilizes a cross-sectoral nexus approach to concurrently focus on the energy and agriculture sectors while providing technical, business acceleration, financing and policy support to its innovators and other stakeholders.

On a broader scale, RE systems are proposed for deserts in the energy landscape, combining wind and solar electricity to serve national and international demands.[47] As these proposals face challenges in terms of infrastructure cost and transboundary cooperation, their near-term implementation appears unrealistic, although the deployment of large-scale CSP plants, for instance in Morocco, is well under way. This dynamic, together with the grand scale of the renewable resources in African and Asian deserts indicates that RE systems play a massive role in decarbonizing the global energy system while using un-productive land.[48]

47 The DESERTEC consortium aims at producing renewable electricity in the Sahara to serve Northern Africa and export markets in Europe (http://www.desertec.org), and the GOBITEC Initiative, which aims to make use of the Gobi desert to generate renewable electricity for Asia (https://gobitecdotorg.wordpress.com).

48 On a small scale, the Sahara Forest Project combines the rehabilitation of land with renewable energy, food and water (from salt water) production (http://saharaforestproject.com).

4. LAND USE PLANNING AND MANAGEMENT FOR RENEWABLE ENERGY SCALE-UP

4.1 Land use conflict and renewable energy development

The previous section indicates that RE can, in some cases, make landscapes more resilient to climate change, especially through agroforestry that combines wood and food crops (Section 3.2) and solar irrigation, drying and refrigeration to reduce food loss (Section 3.4).

Increasing RE deployment also creates conflict over the use of land for energy production.[49] Recent analyses indicate that bioenergy production may severely harm biodiversity, as half of its global potential is concentrated **within** the top biodiversity areas (Santangeli et al., 2016). The potential biodiversity impacts from wind and solar are generally less than those from bioenergy in that two-thirds of the energy generation potential from solar and wind falls **outside** of the top biodiversity areas (Santangeli et al., 2016).

There are many strategies **to avoid or mitigate** potential conflict over solar deployment and lands productively used for other purposes, especially **co-locating** renewable energy systems with food production (e.g., agroforestry, intercropping, among others (Section 3.2)). There also is a large stock of contaminated land unsuitable for agriculture, allowing the application of solar and wind without negative land use effects (Hartmann et al., 2016).[50] For biodiversity-compatible solar development, California implemented its Desert Renewable Energy Conservation Plan,[51] which is under way for large-scale CSP plants in Kenya (Gathu, Odera and Waithaka, 2017).

With regard to conflicts between bioenergy and other land uses that impact biodiversity and local communities, the concept of Agro-Ecological Zoning (AEZ) is one way to resolve tradeoffs through appropriate land use planning (Box 9). This approach has been pioneered in Brazil and is now used in other countries such as Mozambique.[52]

49 Risks to global biodiversity from fossil-fuel production, however, exceed those from biofuel production (Dale, Parish and Kline, 2014). Much of the petroleum exploration activities are projected to occur in remote, fragile terrestrial ecosystems that would remain relatively undisturbed if not for interest in fossil fuel production. In contrast, future biomass production for biofuels is located in areas already substantively impacted by human activity (Dale, Parish and Kline, 2014).

50 See Footnote 19.

51 See http://www.drecp.org/documents

52 The AEZ approach originates from having considered land assessments to determine suitable areas for crops by applying spatially-explicit models, such as geographic information systems (FAO, 1978). It was further developed in collaboration with the International Institute for Applied Systems Analysis (Fischer et al., 2006).

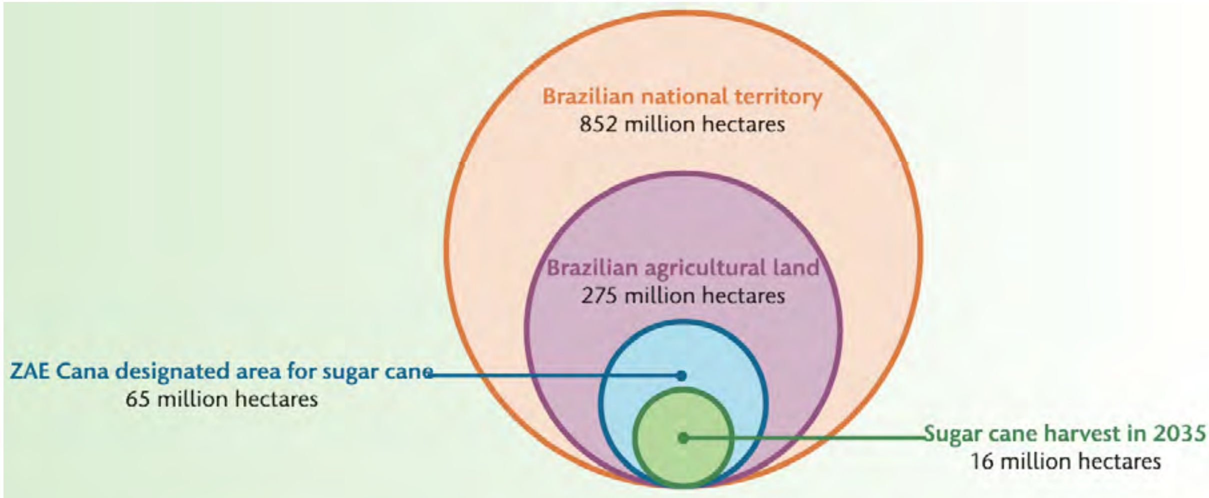
Box 9: Agro-Ecological Zoning (AEZ) in Brazil

In response to concerns that increased biofuel production could displace other agricultural activities and contribute to deforestation, Brazil adopted the Agro-Ecological Zoning (AEZ) approach to identify suitable areas for bioenergy feedstock expansion, taking into account economic, environmental and social aspects and constraints.

In 2007, the Government of Brazil commissioned an AEZ of sugarcane (Zoneamento Agroecológico da Cana, or ZAE Cana (EMPRAPA, 2010a)), followed by palm (EMPRAPA, 2010b), to keep it from encroaching on the Amazon forest region. AEZ work was led by the Ministry of Agriculture (through its research agency, EMBRAPA) and the Ministry of the Environment, and is supported by several other federal agencies and universities. These programs were translated into law through presidential decree (GoB, 2009, 2010) - which exclude the Amazon and the Pantanal and Paraguay River Basin - for sugarcane plantations by barring farm loans for sugarcane and denying environmental permits for new sugar or ethanol plants in these regions.

ZAE Cana has identified underutilized pasturelands where sugarcane production could be sustainably expanded, for instance by increasing cattle densities on other pastures (Andrade and Miccolis, 2011). Under its guiding criteria, 7.5 percent of Brazil's national territory is suitable for sugarcane production (Figure 4) and only 25 percent of this potential area is expected to be utilized for sugarcane in the next 20 years (IEA and FAO, 2017). Meanwhile, the AEZ approaches in Brazil also address eucalyptus, which may serve as a feedstock for woody bioenergy export (IINAS and CENBIO, 2014).

Figure 4: Agro-ecological zoning: designation of land suitable for sugarcane production in Brazil



Source: IEA and FAO (2017).

FAO has produced and refined guidelines and tools to assess the local, regional and national impact of bioenergy feedstock production projects, to be used before and after project implementation.[53] Another key tool to ensure that land rights are respected and enforced is the *Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security* (CFS, 2012), which encourage the periodic review of agreements, ensuring that they are properly understood and that indigenous people and other vulnerable groups are provided with information and support so they can participate effectively.

Certification schemes (Section 6.2) often refer to best practices in management. Such best management practices assist farmers to achieve higher yields as well as higher incomes, both of which contribute to an improved food security status.

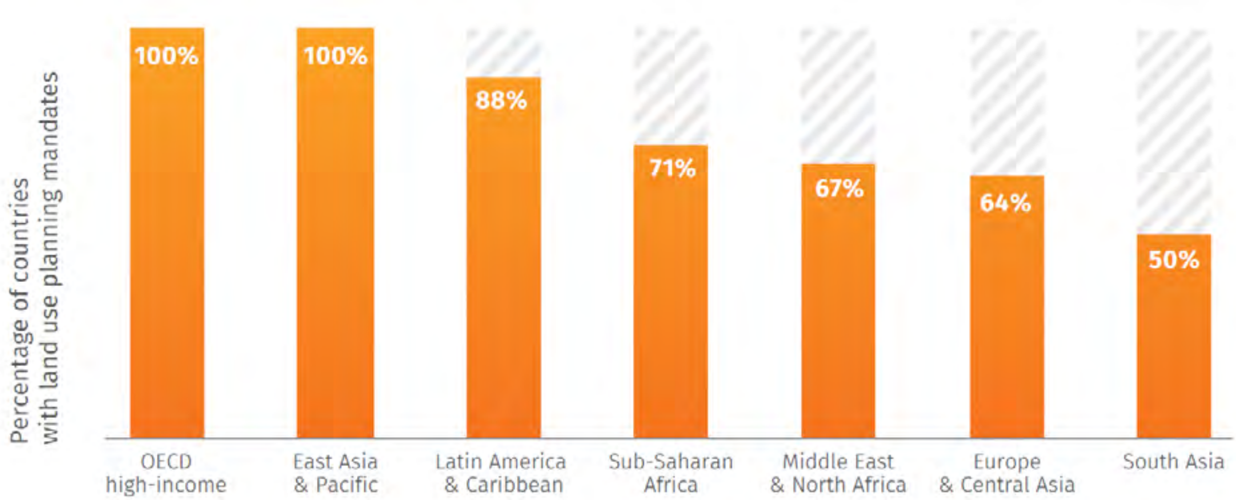
For onshore wind development, many countries use zoning strategies to avoid conflict with avifauna and biodiversity in general, aesthetic considerations in landscapes, and regulations for noise pollution (e.g., distance to settlements, see IEA, 2014). Similar approaches have been developed for offshore wind siting, e.g., in the North Sea (EEA, 2009).

53 See, for example, Fritsche et al. (2010b); FAO and UNEP (2011); Beall, Cadoni and Rossi (2012), Rossi (2012) and FAO (2014b).

4.2 Land use planning and renewable energy development

These approaches to harmonize large-scale and decentralize RE deployment with land use require planning. Current practices in that regard are regionally and significantly different (Figure 5).

Figure 5: Land use planning mandates in different world regions



Source: World Bank (2017).

Land use planning encourages the assessment of current and potential land uses in a territory and the adoption of those that best meet people's needs, while safeguarding valuable resources for future generations. Soil quality data provide useful information for governments, farmers and other stakeholders to monitor the impact of agricultural activities and inform land management decision-making and farming practices. While land use planning is mandated in all high-income member countries of the Organisation for Economic Co-operation and Development, as well as in East Asian and Pacific countries, it is less common in other regions such as Africa and South Asia, except Nepal and India (World Bank, 2017).

In India, where land use planning is regulated by state-level governments, two states (i.e., Odisha and Maharashtra) mandate developing land use plans. India is also implementing a national soil monitoring program that aims to provide farmers with relevant data (World Bank, 2017). With regard to energy and land use, it is important to differentiate between the centralized (non-renewable) technologies that require fuel and other resources to be delivered to the production facility and distributed RE technologies that rely on either on-site fuel and/or use the energy locally, significantly reducing the need for transportation and transmission infrastructure. Land use planning should consider the implications of the entire life cycle of different technologies and fuels (Kaza and Curtis, 2014). An important example combining land use planning with bottom-up activities to rehabilitate degraded land and to provide more ecosystem services is the Great Green Wall in Northern Africa (Box 10).

Box 10: The Great Green Wall for the Sahara and the Sahel Initiative

In 2007, 11 African countries adopted the Great Green Wall for the Sahara and the Sahel Initiative (GGWSSI), and in 2012, a harmonized strategy for the GGWSSI was adopted (AU, 2012).[54] Today, many Sahelian and Saharan countries (Algeria, Burkina Faso, Chad, Djibouti, Egypt, Eritrea, Ethiopia, the Gambia, Mali, Mauritania, Niger, Nigeria, Senegal, Sudan), as well as various international partners, United Nations entities, non-government organizations and the scientific community are involved in the GGWSSI, including the EU Delegation to the African Union Commission (FAO, 2016b).

The GGWSSI's aims do not relate to "a wall of trees" crossing the Sahara; rather, it provides multisector initiatives and interventions to ensure natural resource conservation and protection with the aim of fighting poverty. Its goal is an integrated development of economically valuable plant species adapted to drought conditions, as well as basic social infrastructures managed by local inhabitants (individually or in groups), private producers, local authorities or forestry services (Bellefontaine et al., 2011). It reflects a policy vision about a "green, fertile and prosperous Africa rid of famine and images of malnourished children" (AU, 2012), aiming at reversing land degradation trends by 2025 and transforming the Sahara and the Sahel into rural production and development hubs by 2050 (UNCCD, 2016).

Today, approximately 15 percent of the targeted 7,000 kilometers of trees has been planted (Palmer, 2016). Senegal has reclaimed more than four Mha of land along the Great Green Wall. They have planted more than 27,000 ha of indigenous trees that do not require watering. Many animals that had disappeared from those regions are reappearing — animals such as antelopes, hares and birds which, for the past 50 years, were not seen.

Figure 6: Participating countries and focus areas of the Great Green Wall

Source: UNCCD (2016).

54 For details, see http://www.greatgreenwallinitiative.org

The GGWSSI also has raised interest in Southern Africa for a Great Green Wall for Southern Africa (World Bank, 2016).[55] Earlier activities on a Great Green Wall for China (Bellefontaine e al., 2011) indicate that the concept is not only an African one, and that much learning on appropriate and sustainable implementation which, like Africa, will be required in China (Jian, 2016).

55 See also http://clubofmozambique.com/news/southern-africa-join-great-green-wall-august-30-2016/

5. LAND DEGRADATION NEUTRALITY AND SUSTAINABLE ENERGY FOR ALL

The previous sections indicate that the linkages between RE development and land use are substantial, and that activities such as agroforestry, phytoremediation and use of degraded land for bioenergy are instrumental to improve land use in the future. These activities appear as potential contributions to achieve land degradation neutrality (LDN), reflecting SDG target 15.3 and contributing to SDG 7 and the United Nation's goal of Sustainable Energy for All. Producing sustainable bioenergy while **restoring degraded land** offers significant potential (Section 3.2), although it may face economic challenges due to high investments for preparing initial cultivation and developing infrastructure. Thus, it is worth taking into account how SDG target 15.3 on LDN may drive other SDGs (Figure 7).

Figure 7: **Sustainable Development Goal target 15.3 as a catalyst to achieve other goals and targets**

Source: Akhtar-Schuster et al. (2017)

The **centrality of land** in addressing a number of sustainable development challenges has now been politically recognized (including challenges relating to poverty, food, water and energy security, human health, migration, climate change mitigation, biodiversity loss and so on (Akhtar-Schuster 2017). It matches the core role of (bio)energy and its linkages to land (Table 1). Thus, the implementation of the LDN target may help to realize the sustainable bioenergy potentials from degraded land, and vice versa.

Box 11: What is land degradation neutrality?

Sustainable Development Goal target 15.3 ("By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world") introduces the land degradation neutrality (LDN) concept. LDN strives to maintain or enhance the land resource base and the ecosystem services that flow from it. LDN encourages a dual-pronged effort in sustainable land management to reduce the risk of land degradation, combined with effort in land restoration and rehabilitation to counteract the impacts of land degradation. The Conceptual Framework of the United Nations Convention to Combat Desertification for LDN (Orr et al., 2017) intends to provide a scientifically sound basis for planning, implementing and monitoring LDN. The conceptual framework presents principles to govern implementation of LDN, summarized as follows:

- Maintain or enhance land-based natural capital, protect the rights of land users, and respect national sovereignty.
- For neutrality, the LDN target equals (is the same as) the baseline. Neutrality is the minimum objective: countries may elect to set a more ambitious target.
- Integrate planning and implementation of LDN into existing land use planning processes, and counterbalance anticipated losses in land-based natural capital with interventions to reverse degradation to achieve neutrality.
- Manage counterbalancing at the same scale as land use planning, with "like for like" (counterbalance within the same land type).
- Balance economic, social and environmental sustainability, and base land use decisions on multi-variable assessments, considering land potential, land condition, resilience, social, cultural and economic factors.
- Apply the response hierarchy in devising interventions for LDN: Avoid > Reduce > Reverse land degradation.
- Apply a participatory process: include stakeholders, especially land users, in designing, implementing and monitoring interventions to achieve LDN.
- Reinforce responsible governance: protect human rights, including tenure rights; develop a review mechanism; and ensure accountability and transparency.
- Monitor using the three UNCCD's land-based global indicators: land cover, land productivity and carbon stocks, and use the "one-out, all-out" approach to interpret the result of these three global indicators.
- Use additional national and sub-national indicators to aid interpretation and to fill gaps for ecosystem services not covered by the three global indicators, and apply local knowledge and data to validate and interpret monitoring data.
- Apply a continuous learning approach: anticipate, plan, track, interpret, review, adjust, and create the next plan.

Fundamental to the LDN conceptual framework is the integration of planning for LDN into existing planning processes, as well as the "like for like" approach that requires counterbalancing gains and losses to occur within the same land type. Both have high relevance for energy, as decarbonization will require a massive expansion of RE systems (and respective planning (Section 4.2)). There is much opportunity to restore degraded land through biomass development (Section 3.2.1 and Section 3.3) and to avoid degradation (Section 3.2.2). In the further implementation of the LDN approach (Kust, Andreeva and Cowie, 2016), such options should be taken up.

The ambition of SDG 15.3 (LDN), together with SDG 7 (sustainable energy for all) is to achieve targets by 2030. Now is the time to consider integrated planning for the LDN-supportive development of renewable energy and to reflect on and implement appropriate policies. The following section addresses policies and related governance issues.

6. POLICIES AND GOVERNANCE ADDRESSING LAND-ENERGY LINKS

SDGs, with their targets for sustainable land use and sustainable energy for all, provide the **normative base** for all countries to consider, formulate and implement policies that will achieve these targets. On the road to 2030, the prospective SDG review process by the United Nations High-Level Political Forum intends to convey the extent to which national governments have been successful and where further action may be needed.

There are already examples of how countries should deal with linking land and energy under a sustainability perspective (Section 6.4), and where some private sector activities now exist (Section 6.5), as well as the critical role of civil society (Section 6.6). Before presenting these examples, the issues of measurement (Section 6.1), standards (Section 6.2) and policy coherence (Section 6.3) are addressed.

6.1 Measuring success: land-energy policy indicators

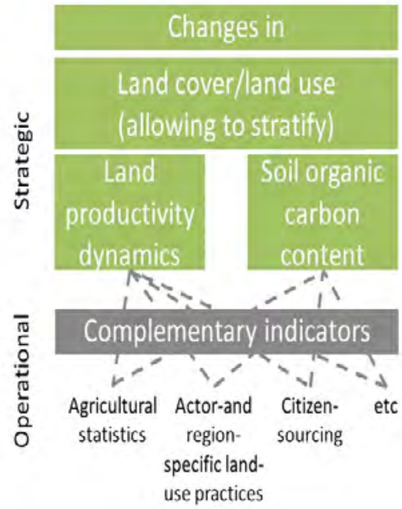
With the SDGs and their 169 targets, the question of how to measure their achievement is important. For the SDGs and targets that relate to energy and land (Table 1), separate indicators are being proposed by the Inter-Agency and Expert Group on SDG Indicators (UNSD, 2016, 2017); that is, the interlinkages of energy and land are not yet reflected.

The land indicators for Target 15.3 (LDN) will require **complementary** measurements on the country/regional level (Figure 8). These activities should be combined with, for instance, the country-level sustainability indicators of the Global Bioenergy Partnership (GBEP, 2011) that encompass LUC and soil organic carbon, providing data on the energy mix, including renewable energy sources and their employment numbers. Furthermore, the role of GHG reporting to the United Nations Framework Convention on Climate Change with regard to the revised requirements under the Paris Agreement on GHG emissions from land use and land use change should be explored.

To facilitate an integrative approach, countries should select respective indicators for the **national implementation** of SDGs, and for this, multi-stakeholder participation is essential, as the value-based character of sustainability requires the full participation of all affected.

In combining the metrics for energy (SDG 7) and land (SDG 15), decision-makers, policy-makers and civil society active in monitoring the SDG implementation should explicitly **identify potential trade-offs between energy and land** and report on synergistic implementation, for instance by using bioenergy as a driver for restoring degraded land. This could allow for additional indicators for food (SDG 2), water (SDG 6), sustainable consumption and production (SDG 12) and climate change mitigation (SDG 13). An integrated approach would be in the spirit of the "energy- food- land-water nexus" (Fingerman et al., 2011; IRENA, 2015b; Mirzabaev et al., 2014; OECD, 2015; UNCCD, 2015), and support the aspiration of SDGs to avoid the silo approach (Weigelt and Müller, 2016).

Figure 8: Land indicators for Sustainable Development Goal 15.



Source: EEA, GLTN, GLII and IASS (2015)

6.2 Standards and certification for sustainable land use

To avoid negative tradeoffs between energy development and land use, sustainability requirements for projects (and their finance) in the form of standards and respective certification are discussed (UNFSS, 2014a, 2014b), and they are already being implemented for biofuels in some countries (Section 6.4). This is especially so for bioenergy.[56]

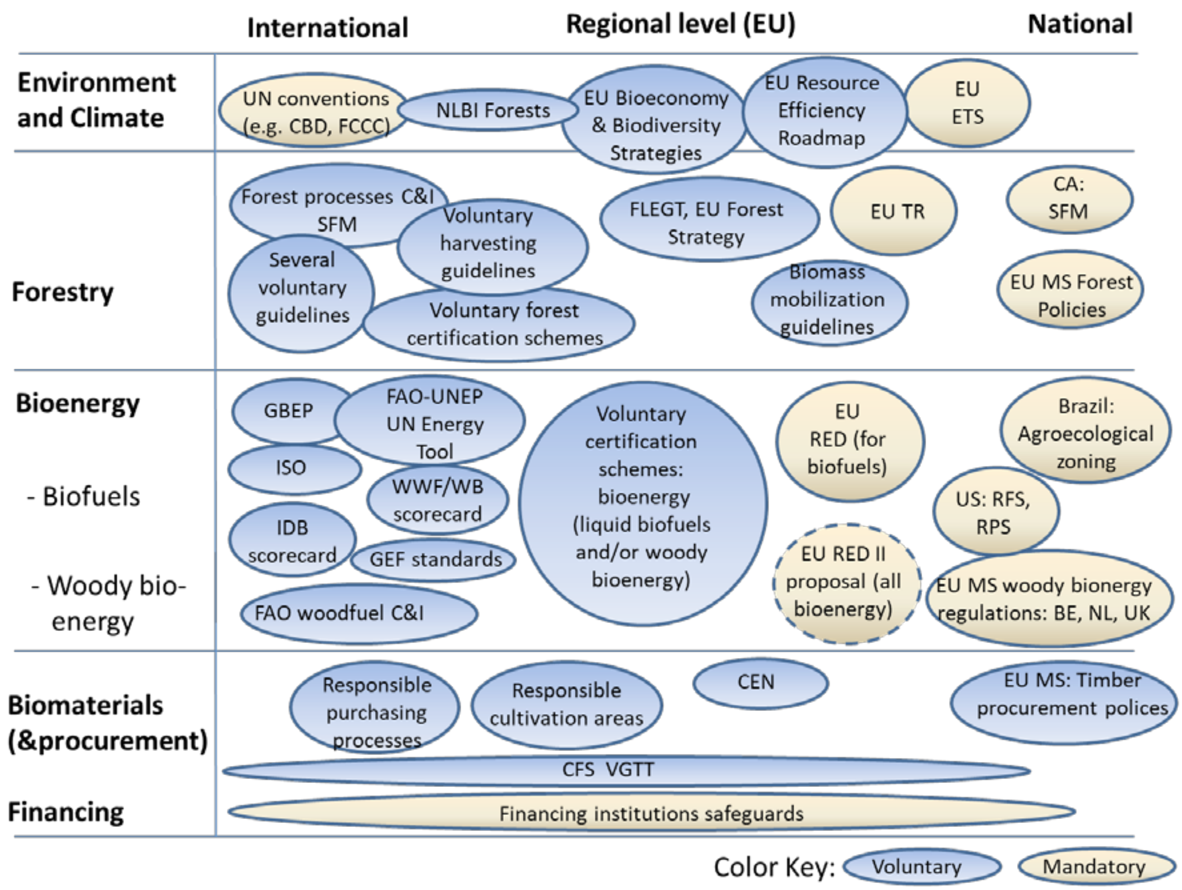
With regard to biofuels, it has been suggested that guidelines for sustainable biofuel development be adopted by countries and used to evaluate the impact and viability of biofuel policy (HLPE, 2013), and that applying sustainability guidelines to bioenergy will help to achieve near- and long-term goals to eradicate hunger (Kline et al., 2017).

There is a significant variety of approaches taken by governments, business, civil society and researchers, and these are partially implemented at different levels (UNFSS, 2014a+b), some of them mandatory although most voluntary (Figure 9). This has raised concerns of the proliferation of standards and schemes that may lead to uncertainty and confusion among market actors.

56 An overview of biomass-related sustainability standards is provided in the literature (Fritsche. 2005-2014; Hunt et al., 2006; Meyer et al., 2016; Robledo-Abad et al., 2017; Thrän and Fritsche, 2016; UN-Energy, 2007; van Dam, 2008-2015; WBGU, 2009)

In sustainable schemes for bioenergy, land aspects are highly relevant (Iriarte et al., 2015), as there is a close relationship to GHG emissions (Box 1), biodiversity, livelihoods and soil. Still, the consideration of land use is not a standard component of "green electricity" and certification systems, and land issues are generally omitted in standards for renewable energy financing, except for bioenergy.

Figure 9: Sustainability schemes relating to biomass and land



Source: Iriarte et al. (2015).

Notes: CBD = Convention on Biological Diversity; FCCC = United Nations Framework Convention on Climate Change; NLBI = Non-Legally Binding Instrument on All Types of Forests; EU = European Union; ETS = EU Emissions Trading System; C&I = criteria and indicators; SFM = sustainable forest management; FLEGT = Forest Law Enforcement, Governance and Trade; EUTR = EU Timber Regulation; CA SFM = Canadian Sustainable Forest Management; MS = member states; GBEP = Global Bioenergy Partnership; FAO = Food and Agriculture Organization of the United Nations; UNEP – United Nations Environment Programme; UN = United Nations; ISO = International Organization for Standardization; WWF = World Wildlife Fund; WB = World Bank; RED = Renewable Energy Directive; US = United States; RFS = United States Renewable Fuel Standard; RPS = Renewable Portfolio Standards; IDB = Inter-American Development Bank; GEF = Global Environment Facility; BE = Belgium; NL = Netherlands; UK = United Kingdom; CEN = European Committee for Standardization; CFS = Committee on World Food Security; VGGT = Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests.

This may change, however. For instance, private sector representatives at the annual World Bank Land and Poverty Conference 2015 called for the creation of a Roundtable on Sustainable Land as a platform to develop a certification standard on Good Land Governance (Myers, 2015). There is growing awareness of land-related problems in bio-based value chains (Section 6.5), and the implementation of SDG 15 could be a key driver to broaden such awareness beyond the biomass community into the larger renewable energy sphere, as well as agriculture. To what extent a global standard for sustainable land use could be conceived and implemented has been the issue of a research project (Box 12), concluding that this should be viewed as an evolving issue, and contributions to that evolution should be part of a broader international process in which research and agenda-setting would be key short-term activities.

To mainstream land use into the energy realm, the UN Rio Conventions (CBD, UNCCD and UNFCCC) should intensify collaboration and seek synergies in joint communication, especially at the level of UN-related scientific bodies (CBD's Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, UNCCD's Science-Policy Interface, FAO's Intergovernmental Technical Panel on Soils, UNEP's International Resource Panel, among others).

This may help to substantiate the scientific base for a more coherent, global standard on the use of sustainable land and its respective certification.

Box 12: Land use and (global) governance: Results from GLOBALANDS

GLOBALANDS[1] has identified three key approaches to improve governance of global sustainable land use:

- Activities to **strengthen** sustainable land use aspects **within existing** global governance systems, such as UN [United Nations] conventions and their respective protocols and implementation programs.
- Better **safeguarding** of sustainable land use for project-level financing of bi- and multilateral development agencies and bodies, with corresponding action for private banks.
- Developing and implementing socially inclusive and actor-oriented **systemic indicators** for sustainable land use to support negotiating the SDGs [Sustainable Development Goals], and to improve safeguarding.

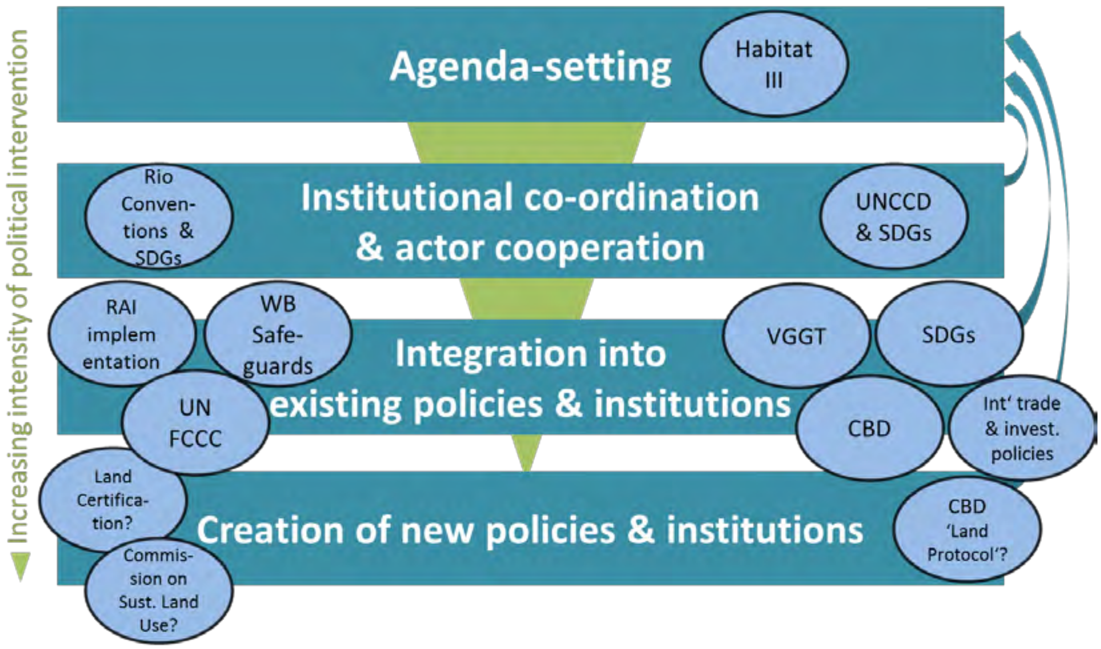
GLOBALANDS has further elaborated **pathways** to strengthen the governance of sustainable land use (Figure 10).

Another key finding of GLOBALANDS is that environmental and social issues of land use should not be viewed as competing but rather as **mutually reinforcing** dimensions of sustainable land use; that is, a focus of future policies should be on integrating these pillars, as well as on collaboration between respective bodies and organizations. To operationalize land tenure and land right aspects in indicators, GLOBALANDS assumes that the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security (CFS, 2012) serve as a framework.

1 This transdisciplinary, three-and-a-half-year project was sponsored by the Government of Germany, and benefits from many international contributions; see www.globalands.org

The GLOBALANDS pathways to strengthen international sustainable land use policy (Figure 10) can overlap and most pathways implicitly involve agenda-setting (Pathway 1). For instance, integrating sustainable land use concerns into pre-existing regulations (Pathway 3) may result in the creation of a new, self-standing standard (Pathway 4). The four pathways can be pursued by governments as well as by non-governmental actors and by public-private networks, either voluntarily or mandatorily as legally non-binding or binding.

Figure 10: Pathways for strengthening international sustainable land use



Source: Fritsche et al. (2015).

Notes: SDG = Sustainable Development Goals; UNCCD = United Nations Convention to Combat Desertification; RAI = Responsible Agricultural Investments; WB = World Bank; VGGT = Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests; UNFCCC = United Nations Framework Convention on Climate Change.

6.3 Policy coherence as a prerequisite

The policy landscape for land use is, as indicated, quite complex at the local, regional, national and international levels, and the energy landscape is a similar multi-level and multi-actor realm. To incorporate these various landscapes into a unified and coherent structure, it will require a Herculean task that is beyond the capacity of current institutions. Sectoral cooperation, nevertheless, is feasible, as demonstrated in the numerous examples documented in this paper.

The implementation of SDGs and their targets requires every country to "enhance policy coherence for sustainable development" - integral to implementation (SDG target 17.14). "Policy coherence is critical to capitalise on synergies among SDGs and targets, between different sectoral policies, and between diverse actions at the local, regional, national and international levels" (OECD, 2016:3).

With that in mind, the short-term objective of policies that address energy-land linkages should be viewed as a matter of raising awareness of those links and substantiating respective scientific knowledge. Furthermore, governance through "loose" arrangements should be taken into account, such as the intersectoral cooperation of national ministries, joint projects with UN entities, and the development and implementation of voluntary guidelines and agreements between governments, businesses and civil society (IASS, 2015).

6.4 Examples of government policy

Most countries have licensing and siting regulations in place to consider the **local** direct land use effect of a coal power plant, solar PV panels or wind farm. Many have implemented energy policies that foster RE systems, although few have linked them with land regulations, with fewer having considered the indirect and wider impacts of energy systems. The one exception is **biofuels**. Several EU member states - including the EU in its entirety - Switzerland and the United States have introduced comprehensive requirements on the sustainability of biofuel feedstock and its conversion, with the core elements of GHG emission reduction and appropriate land use. Developing countries, such as China and South Africa, have biofuel mandates that exclude food crops, such as maize, due to food security considerations.

The EU's 2009 Renewable Energy Directive (RED), which requires all member states to achieve a 10 percent renewable transport fuel share by 2020 (EU, 2009), failed to consider indirect land use changes at inception (Box 1), instead banning biofuel feedstock that originated from land converted to feedstock cultivation subsequent to 1 January 2008, and from biodiversity-rich grassland and primary forests.

In the 2015 RED revision, the EU introduced a cap of 7 percent on biofuels from food crops for the 2020 renewable transport fuel target of 10 percent to reflect possible ILUC risks (EU, 2015).[57] The European Commission's 2016 proposal for a RED recast further reduces this cap to 3.7 percent by 2030 (EC, 2016b, 2016c), and is significant as it extends the scope of sustainability requirements to include **all** bioenergy.[58]

Several European countries, as well as many bilateral and multilateral development programs, have regulations designed to promote sustainable sourcing of bioenergy feedstock. Germany's renewable electricity law had originally promoted land-intense biogas electricity derived from crops such as maize, although this was changed in 2012: Biogas from residues and waste is now the focus. Belgium, Denmark, the Netherlands and the United Kingdom also have sustainability requirements for bioenergy which, to some extent, reflect land use issues albeit not explicitly.

A similar pattern exists for government policies regarding the financing of renewable energy in broad terms, domestic and internationally. Bilateral and multilateral development banks[59] and specific funds, such as the Global Environment Facility and the Green Climate Fund have safeguarding policies for RE investments. These include the requirement of an environmental impact assessment at the project level. The assessments consider direct land use effects as part of the environmental analysis, excluding the off-site impacts of project life cycles.

57 Much of this quota, however, comes from imported soybean and palm oil, resulting in possible food security impacts (Section 3.1.3). Crop calories used for biofuels increased from 1 percent to 4 percent between 2000 and 2010 (Cassidy et al., 2013). In Argentina, soybean biodiesel production reached 2.7 million tons in 2016, 50 percent more than the previous year. Argentina is expected to resume soybean exports to Europe following a court ruling that ended anti-dumping duties (Sapp, 2016), and soybean oil is projected to supply approximately 10 percent of the EU's biofuel production by 2020 (Laborde, 2011).

58 Note that the 2016 RED recast proposal is still being negotiated between the European Parliament, Council (representing member states) and European Commission. A final decision is expected in late 2017.

59 Most notable are the World Bank and its private sector investment arm, the International Finance Corporation, as well as the multilateral regional development banks, including the Asian Development Bank, African Development Bank, European Bank for Reconstruction and Development, European Investment Bank and Inter-American Development Bank. Furthermore, most bilateral banks and a multitude of national agencies and aid development programs are active in supporting RE projects, with many having environmental and social safeguard policies similar to those of the World Bank/International Finance Corporation.

6.5 Private sector initiatives

Given the lack of awareness and governance in terms of the land-energy nexus, there are few private sector activities that explicitly address these links (Klink and Wolff, 2015). One is the promising dynamic in biomass-related value chains, such as deforestation-free policies and sustainable biomass sourcing.[60]

Given that RE systems are growing at a global scale (IEA, 2016; REN21, 2016), land-related issues will gain prominence, civil society (Section 6.6) and the scientific community will continue to highlight tradeoffs. On the road to becoming more mainstream, RE businesses will need to consider and balance stakeholder and shareholder interests, as occurs in the biomass-related value chains and in the divestment campaigns that target fossil-fuel industries.

In general, there remains a disassociation between private sector sustainable energy activities and those relating to land.[61] Interestingly, the Finance Initiative "principles for positive impacts finance" under the United Nations Environment Programme (UNEP-FI, 2017) omit reference to land, and the work program of the World Business Council for Sustainable Development continues to isolate energy activities from those of agriculture, food and land.[62] This clearly demonstrates that the interlinkages of energy and land are yet to be mainstreamed into private sector activities.

60 A large variety of biomass-related voluntary sustainability standards and certification schemes are in place, most of which were initiated and governed by a mix of civil society and private sector stakeholders (van Dam, 2008-2015; Iriarte et al., 2015). The Roundtable on Sustainable Biomaterials currently provides the most comprehensive standards with a rather elaborate concept in terms of dealing with land-related issues (www.rsb.org). With regard to the private sector, the Sustainable Biomass Program primarily represents large electric utilities in Europe, having developed a comprehensive certification system for woody material used for co-firing (https://sbp-cert.org).

61 There is growing interest in and evidence of private sector involvement in protecting biodiversity and achieving reforestation, as well as ensuring land restoration and LDN. The linkages to and integration of energy, however, are absent in most cases, although there is significant potential to include them (Section 3.2.1 and Section 3.3).

62 See the World Business Council for Sustainable Development's presentation of work on energy (www.wbcsd.org/Overview/Our-approach/Energy), agriculture, food and land (http://www.wbcsd.org/Overview/Our-approach/Food-and-land-use).

6.6 The role of civil society

Undoubtedly, energy and land are crucial sustainability components, and civil society – including civil rights movements, consumer organizations, faith-based groups, labor unions and environmental and development NGOs – is at the forefront. While this may be the case in terms of biofuel and bioenergy in general, civil society is exceptionally active at local and regional levels in terms of participating in siting, design and implementation of geothermal and larger solar plants, as well as wind farms, and especially large hydropower schemes.

The SDG ambition to "leave no one behind" and the inclusive approach required for implementation provides a key role for civil society in the energy transition going forward. It is essential that land-related tradeoffs and relevant synergies are intrinsic. Given that bioenergy is the major component of RE, not only today but also in the near future, and the fact that bioenergy is land-intensive, it is crucial that there is interaction and discussion with civil society on these linkages. Ongoing efforts of IEA, IEA Bioenergy and IRENA to reach out to civil society should be strengthened in their attempts to define sustainable pathways for biomass development. These efforts must be collaboratively supported by other land-related processes and, not least, in terms of raising awareness.

7. SUMMARY AND CONCLUSIONS

This paper synthesizes the current knowledge on the **land-energy nexus** in terms of land-based ecosystem services, while applying the SDGs as a **normative framework** for analysis. Energy's current land footprint is a result of non-renewable (primarily fossil fuel) energy, representing around 90 percent of global primary energy use. Land impacts originate mainly from exploration, extraction and conversion (e.g., coal mining, oil refineries, power plants) and, to a smaller extent, from infrastructure (e.g., pipelines, storage, transmission). Compared to other land uses of agriculture, forestry, mining and urban settlements, direct land use for energy production is small, at approximately 2 percent of total global land area. Fossil fuel impacts the land for a longer period compared to sources of renewable energy. It is expected that with the projected growth in global energy demand and enhanced fossil fuel recovery technologies, the intensity of **non**-renewable energy sources on land use will increase. The exploitation of fossil fuel resources located in fragile environments (e.g., the Arctic) and highly biodiverse areas (e.g., rainforests) will then increase land impacts.

Given the call for global decarbonization by the Paris Agreement, **renewable** energy will continue to expand at a faster rate, resulting in significant land use impacts in the future. While fossil fuel use is only restricted by the size of and access to the resource (including cost and the CO_2 budget), renewable energy is mostly **restricted by land use allocation**.

This paper compares land intensity and the impact of **all** terrestrial energy forms.[63] With regard to renewables, the following are the key points:

- **Bioenergy**, including biofuels, is a significant land-intensive option, although its actual land use - including its environmental and social impact - is more site- and context-specific compared to other energy types, as well being less long term. Bioenergy from crops has a direct land footprint of up to several hundred m2/MWh, while that relating to biogenic residues and waste is close to zero.
- **Marginal and degraded land** can deliver bioenergy, with benefits to biodiversity, carbon sequestration and rural livelihood. This, however, is subject to environmental and social safeguards. Furthermore, feedstock from such land tends to be more costly than that grown on arable land.
- When improperly planned and implemented, rapid large-scale bioenergy expansion potentially increases GHG emissions and poses the risk of food insecurity. If adequately designed, bioenergy will contribute to a reduction of GHG and promote land rehabilitation, market resilience, infrastructure and rural development. Perennial crops, such as grasses and SRC that are integrated into the agricultural landscape (e.g., agroforestry, intercropping) will benefit biodiversity, carbon sequestration and water availability.
- **Hydropower** is a key RE source, although it tends to flood the land when water is stored behind dams. Changes river flows impact on up- and down-stream ecosystems. While Its land use intensity may be limited (5-10 m2/MWhel), especially with regard to large systems, it has the potential to increase to well above 500 m2/MWhel in smaller plants, being a similar order of magnitude as the bioenergy from crops.
- **Solar energy** for hot water and small-scale PV for electricity typically rely on rooftop systems without the need for land use. Large-scale PV and CSP have land footprints in the order of 1-10 m2/MWhel.
- **Wind energy**, with a land footprint in the order of 1 m2/MWhel, is the lowest land use RE option.

To what extent the overall land use of RE is more favorable than that of non-renewable sources depends on the mix of renewables, their siting, method of deployment and maintenance/management. Innovative deployment of renewables (e.g., co-location) will reduce the use of land and avoid landscape disturbances caused by fossil and nuclear energies.

63 This paper excludes geothermal energy, based on its high site-specificity. Marine energy, aquatic and land-based algae and non-biomass renewable fuels are also excluded due to their early stage of development (Footnote 9).

The conclusions and recommendations that emerge from the above summary are as follows:

- The impact on land use of **renewable** energy technologies is potentially significant. **Adequate planning and integrative strategies** are essential to avoid negative land tradeoffs. In assessing these tradeoffs, avoidance of land use from non-renewable energy, especially coal, should be taken into account.
- **Mini- and micro-grids** based on RE will foster rural electrification, improve agriculture and food processing, and benefit rural land use and livelihoods. These options, therefore, **should be vigorously promoted**, particularly in the presence of clear regulations and incentives that take into account the benefits in an effort to develop markets and create a vibrant business environment.
- Bioenergy **requires integration** into the landscape (e.g., agroforestry, intercropping) to ensure land use efficiency, particularly in terms of land-intense biomass, at the same time taking into account the positive water impacts of biomass systems and biogenic residues and waste.
- Bioenergy from **marginal and degraded land** should be recognized as a key to achieving LDN when combined with sustainability safeguards. Since feedstock production on these lands is more costly than fertile land crops, implementation will depend on economic incentives and regulations.
- Until recently, there has been little deliberation on the implementation of SDGs and the energy-land synergy in terms of solar/wind co-location, agriculture and bioenergy integration, as well as the significant potential of marginal and degraded land. This applies also to agroforestry, intercropping and biogenic residues and waste. **It is recommended**, therefore, that this analysis be extended to include the SDG perspective so as to reflect the complexity and interdependencies between the various energy supply options and technologies, avoiding at the same time the ranking of options that are based on simple metrics, such as land use per unit of output. It is essential that the integration of systems be considered, especially in terms of the high allocation of variable RE systems and the beneficial role of bioenergy.
- **Governance** of sustainable land use remains fragmented in terms of public and private sector policies, and the integration of energy is inadequate. The benefits of bioenergy with sustainability standards **need showcasing in an effort to mainstream them** with other renewable energy sources. In this instance, the role of civil society as a catalyst and promoter is essential.
- Given the 2030 timeframe for the SDGs, and 2050 for decarbonizing the global energy system, it is imperative that knowledge and research of land-energy links be improved. The collaboration of sectors and stakeholders at global level should include not only the Rio conventions and their scientific bodies and secretariats, but also agencies such as FAO, IEA, IRENA, UNDP and UNEP.
- The **private sector** is in need of clear signals and guidance in order to extend national and international low-carbon roadmaps to include the land issues in the new IEA Bioenergy Roadmap intends (IEA, 2017). Future roadmaps and guidance documents for e.g., solar and wind from international entities (e.g., IEA, IRENA) should provide practical approaches and highlight zoning strategies for RE development, as well as the benefits of landscape integration and co-location.
- Finally, bilateral and multilateral **financing institutions** that promote the use of renewable energy (e.g., World Bank and regional development banks, Global Environment Facility, Green Climate Fund, LDN fund and bilateral donors) **should spearhead projects and programs that integrate land and energy and develop and implement the most appropriate sustainability standards** that reflect the potentials of sustainable bioenergy and other renewable energy sources.

The implementation of the SDGs in an integrative and inclusive approach is a valuable opportunity for governments to take into account these conclusions and recommendations. For this, governments must collaborate with civil society, the private sector and the scientific community to deliver a sustainable global energy system in all countries - kiloWatt by kiloWatt and hectare by hectare.

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