UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Renewable Energy for Inclusive and Sustainable Industrial Development

The Case of Biomass Gasification

Acknowledgments
This publication was prepared by Diego Masera, Chief of the Renewable and Rural Energy Unit of United Nations Industrial Development Organization (UNIDO) and André Faaij, Distinguished Professor Energy System Analysis - University of Groeningen and Academic Director Energy Academy Europe with the collaboration of Sunyoung Suh, Caroline Zimm and Jana Imrichova from UNIDO.

This discussion paper is based on a compilation of material from the assessment work of the IPCC-SRREN report, the book: Renewable Energy for Unleashing Sustainable Development (Colombo, Bologna, Masera, Springer 2013), the IEA Bioenergy Review and several technical papers.

Vienna, 2014

Preferred citation: MASERA, D., FAAIJ A.
Renewable Energy for Inclusive and Sustainable Development. The Case of Biomass Gasification. UNIDO, 2014.

DESIGN red hot 'n' cool, Vienna

Renewable Energy for Inclusive and Sustainable Industrial Development

The Case of Biomass Gasification

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION


10
GASIFIER
HOT DO NOT TOUCH
13

Table of Contents

Executive Summary

Biomass is an essential renewable energy source for a low carbon energy future on a global scale. Biomass resource potentials are large enough to deliver about a quarter (i.e. 200-300 EJ) of the world's future energy supply. Bioenergy has a significant greenhouse gas (GHG) mitigation potential, provided that the resources are developed sustainably and that efficient bioenergy systems are used. Certain current systems and key future options including perennial cropping systems, use of biomass residues and wastes and advanced conversion systems together deliver 80 to 90% emission reductions compared to the fossil energy baseline.

Bioenergy has complex societal and environmental interactions, including climate change, biomass production and land use. The impact of bioenergy on social and environmental issues (e.g. health, poverty, biodiversity) may be positive or negative depending on local conditions and the design and implementation of specific projects. Many conflicts can be reduced, if not avoided, by encouraging synergisms in the management of natural resources as well as the agricultural and livestock sectors. Good governance of land use can also lead to rural development and contribute to poverty alleviation and increased energy security.

UNIDO's global mandate on "Inclusive and Sustainable Industrial Development (ISID)" aims to promote sustainable and resilient economic and industrial growth for poverty reduction that goes hand in hand with economic, social and environmental dimensions of sustainable development. In this context, UNIDO has long recognised that Renewable Energy Technologies (RETs) are a key component to achieve sustainability and therefore they have to be supported and promoted especially for distributed energy solutions, mini-grids and industrial applications. An industry sector that is solely dependent on energy from fossil fuels cannot be considered sustainable. In the long run, the volatile price of fossil fuel, coupled with continued environmental degradation from extraction activities and combustion-induced GHG emissions, will impinge on economic, social and environmental goals. RETs, as a substitute for fossil suels, provide various benefits which greatly contribute to achieving inclusive and sustainable industrial development.

There is a wide opportunity for RETs use in industry. Companies can use RETs either as consumers, producers or both at the same time by becoming industrial prosumers of renewable energy. In particular agro-industries have a good potential to become industrial prosumers by using their own waste to generate heat and power for their own needs and to sell the excess to the neighbouring community or grid. Bioenergy and in particular biomass gasification is well suited for this purpose.

Small scale gasification technologies are technically and commercially proven for heat generation and are suited for various industries where biomass is available and process heat is required. Small scale gasification systems for power generation (or CHP operation) offer the prospect to combine rural development opportunities due to electrification, combined with use of locally available biomass fuels and fit very well in many sustainable development schemes. The technology does however require further development and optimisation. Recent experiences, with this type of technology, such as in Cuba, are promising.

Once commercial, biomass gasification will contribute to an inclusive and sustainable industrial development by allowing local industries to see energy as an income opportunity, local green job creation, development of industrial prosumers and a key technology for distributed energy generation and therefore also for energy access.

Introduction

Energy drives human progress, and now more than ever the world needs to ensure that the benefits of modern energy services are available to all and provided as cleanly, safely, and efficiently as possible. The transition to sustainable energy systems represents one of the key challenges of our global economy and, at the same time, the opportunity to rethink our energy models. Renewable energies have a pivotal role to play within this challenge (Colombo, Bologna, Masera; Springer 2013).

Bioenergy is energy derived from biomass, which can be deployed as solid, liquid and gaseous fuels for a wide range of uses, including transportation, heating, electricity production, and cooking. Bioenergy has a significant GHG mitigation potential, provided that resources are developed using sustainable practices and that efficient bioenergy systems are used (Chum et al. 2011). Bioenergy systems can cause both positive and negative effects and their deployment needs to balance a range of environmental, social and economic objectives that are not always fully compatible. The consequences of bioenergy implementation depend on a) the technology used; b) the location, scales and pace of implementation; and c) what business models and practices are adopted - including how these integrate with or displace the existing land use.

Existing agro-industries represent a source of biomass from residues but also an opportunity for renewable energy generation and energy access; in this paper the concept of industrial prosumers is introduced as: *an industry that produces and makes use of renewable energy sources such as solar, wind, bioenergy, etc. to supply a portion or all of its onsite energy needs. In many cases, this includes selling excess energy or electricity to the national/local grid or to the surrounding community.* With the right policy and regulatory conditions, industrial prosumers could play an increasingly important role in the transition to a more inclusive and sustainable energy system in the decades ahead. This paper focuses on industrial prosumers working with biomass residues.

In order to generate electricity, biomass can be combusted, gasified, biologically digested or fermented, or converted to liquid fuels to propell a generator. Several research institutions and international agencies rate biomass as one of the cheapest available renewable energy sources for power generation. Furthermore, conversion from biomass to electricity is a low- carbon process as the resulting CO_2 is captured by plant regrowth. In contrast with solar PV or wind power, biomass power technology can generate electricity on demand at any time, as long as a sufficient supply of biomass stocks is assured. Many agricultural and forest product residues can provide feedstock for energy conversion without increasing land requirements. Local farmers can generate additional income by providing biomass fuels for small local power plants.

The gasification technology is principally well suited for small power plants ranging from 10 kW to over 100 kW. Appropriate gasifier systems with internal combustion engines can produce 1 kWh of electricity from 1.1 – 1.5 kg wood, 0.7 – 1.3 kg charcoal, or 1.8 – 3.6 kg rice husks. Assuming the biomass originates from renewable production – regardless of whether planned forestation or natural regeneration - it would be a perfect, nearly CO_2 neutral, renewable energy source.

Hence, this technology is a good solution for many initiatives and projects in times of the climate change debate. The general features of the technology are indeed promising: in contrast to a PV system or a wind mill, electricity can be produced at any desired time given the availability of the required biomass. Nevertheless, this technology is still at an early commercial state and therefore widespread deployment has not been achieved yet.

Part I
Renewable Energy for Inclusive and Sustainable Industrial Development (ISID)

1.1. Renewable energies to promote ISID

Energy has been deeply linked to the history of mankind and tied to its development. Some of the natural resources which are today referred to as renewable energies, such as biomass, solar heat, wind power, tidal and wave energies, have been known for centuries. Among all the energy sources, renewable energies were the first to be used to satisfy human needs. Today, for the poorest people, the opportunity to overcome the development divide strongly depends on the possibility to access energy to transform their products and develop the local economy. In this context, renewable energies, in particular through distributed generation, represent an opportunity for local populations to cover their energy requirements, create employment and income generation without destroying the environment.

Renewable energy allows an inclusive and sustainable industrialization which drives human development; from job generation to economic competitiveness, from strengthening security to empowering women. Now more than ever, the world needs to ensure that the benefits of energy are available to all and that energy is provided as cleanly, safely and efficiently as possible.

In the context of the current climate crisis and the obligation to provide economic development and energy access to a fourth of the global population, the need for a clear, stable and predictable energy policy that focuses on a low carbon renewable energy, the best use of local resources and a sustainable industrialization is paramount.

The productive use of energy for income generation must be promoted in order to break the vicious circle of low income leading to poor access to modern energy services, which in turn puts severe limitations on the ability to generate higher incomes (Colombo, Bologna, Masera, Springer 2013).

Faced with frequent power outages and low power quality from the national grid or simply located far from the limited national grid of most developing countries, many industries in the developing world produce part or all of their electricity needs with on-site diesel generators. In many cases, these rely on either diesel or heavy fuel oil, used either as a primary power supply source, or as an automatic back up when the national or regional grid network fails.

Until recently, the most cost-effective way of doing so was via onsite fossil fuel based technologies. However, these fossil fuel-based options exhibit a number of undesirable characteristics, such as high operating costs, significant price volatility, as well as greenhouse gas and other emissions. The recent trends show a shift toward use of Renewable Energy Technologies (RETs), as they become an economically attractive option for electricity supply in a growing number of countries in the world.(IRENA (2014). "REMAP Project," Available at: http://irena.org/remap/).

In particular, industries with onsite waste-to-energy generation potential are therefore promising candidates to drive this transition. Agro-industrial Small and Medium Enterprises (SMEs), for example, such as rice or sugar mills, have significant potential for deployment of cost-effective renewable electricity and renewable thermal projects which can supply on-site energy needs while providing opportunities to generate additional income and benefit the local community through the sale of excess energy. Renewable energy projects developed by agro-industrial SMEs can yield numerous co-benefits for both owners and the local community, including reduced energy costs; increased energy access in rural areas; avoided local air pollution and GHG emissions; reduced waste; improved health and sanitary conditions; creation of new income-generating opportunities; and local economic benefits such as creating higher-skilled jobs and facilitating development of clean energy industries.

Such industries in rural areas can thus play an important role in supporting the Sustainable Energy for All (SE4ALL) objectives of universal energy access and increasing renewable energy utilization, and in particular in furthering rural electrification. With the right policy incentives and local energy distribution infrastructure, SMEs with RET application potential in site can be incentivized to install energy production systems that can serve a larger portion of their own energy needs while providing excess generation (or heating and cooling supply) to the local community.

Access to sustainable energy provides numerous economic, social, and environmental benefits: for example, lighting has been shown to significantly improve productivity and facilitate education in rural areas; cooling applications are critical for health and food storage; and heating and cooking with sustainable energy reduces reliance of sustainable energy, businesses can thus take a leadership role in furthering sustainable development and addressing local and global social and environmental challenges (Couture, Masera, UNIDO 2014, forthcoming).

1.2. UNIDO's approach

UNIDO's global mandate on "Inclusive and Sustainable Industrial Development (ISID)" aims at promoting sustainable and resilient economic and industrial growth for poverty reduction that goes hand in hand with the economic, social and environmental dimensions of sustainable development.

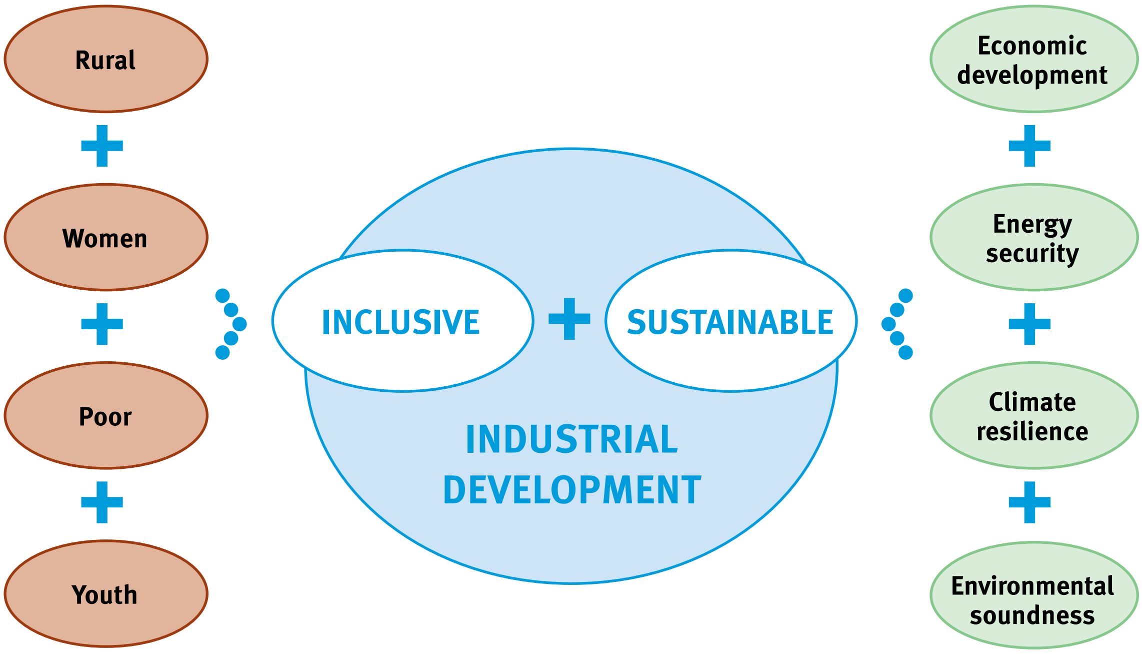
Industry plays a decisive role in stimulating economic growth. Global experiences have shown that countries have reached high levels of socio-economic development by having a developed and advanced industrial sector. However, industrial sector growth is conventionally linked with excessive environmental pressures such as resource depletion, pollution at the local and regional level and negative impacts in terms of climate change. UNIDO is promoting ISID as part of a broader strategy to harness the full potential of industry's contribution to achieving sustainable and equitable human development (UNIDO 2014 Inclusive and Sustainable Industrial Development," Available at: http://www.unido.org/fileadmin/user_media_upgrade/Who_we_are/Mission/ISID-Brochure-LowRes1_EN.pdf).

In order to minimise environmental damage while meeting the global objectives of eradicating poverty and reducing income disparity, industrial development must become sustainable and inclusive. Thus, UNIDO aims to achieve ISID which means that:

- Every country achieves a higher level of industrialization in their economies, and benefits from the globalization of markets for industrial goods and services.
- No one is left behind in benefiting from industrial growth, and prosperity is shared among women and men in all countries.
- Broader economic and social growth is supported within an environmentally sustainable framework.
- The unique knowledge and resources of all relevant development actors are combined to maximize the development impact of ISID.

The below figures provides an overview of the dimensions of ISID and the contribution of renewable energies in its promotion.

Figure 1 | Dimensions of Inclusive and Sustainable Development

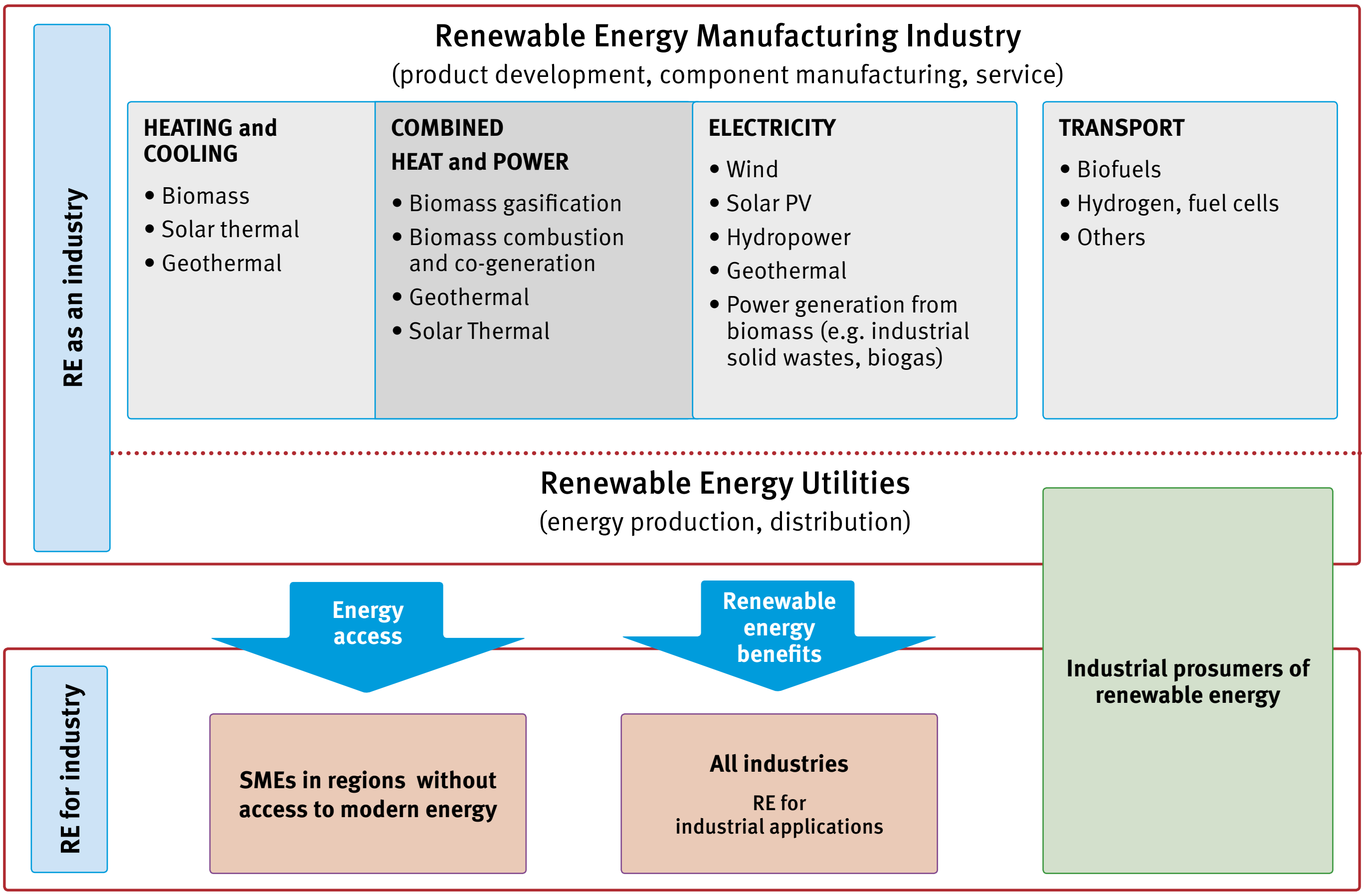


An industry sector that is solely dependent on energy from fossil fuels cannot be considered sustainable. In the long run, the volatile price of fossil fuel, coupled with continued environmental degradation from extraction activities and combustion-induced greenhouse gas emissions, will impinge on economic, social and environmental goals. RETs, as a substitute for fossil fuels, provide various benefits that greatly contribute to achieving ISID. The contribution of RETs to industry and industrial development can be summarised as follows:

1. Allowing energy to become an additional income opportunity for industries with potential to produce renewable energy on site;
2. Reducing the overall environmental impact of industries;
3. Creating local green jobs;
4. Enabling the establishment of 'green industries';
5. Manufacturing of renewable energy components to the inclusion of RETs in the utility industry;
6. Increasing local productive activities through providing sustainable energy access;
7. Promoting renewable energy for industrial applications;
8. Developing the local economy by adding value to local resources and reducing dependency on imported sources of energy.

The below figure gives a detailed picture of renewable energy as an industry itself and renewable energy for industry, and how industrial prosumers of renewable energy are a linkage between these two areas. Further explanation on industrial prosumers will be provided in the following section.

Figure 2 | Renewable energy as an industry and for industry



Access to sustainable and affordable energy can therefore play an important role in achieving ISID, as energy (electricity, as well as heating and cooling applications) is a critical input in numerous industries. Access to reliable, efficient, and affordable energy is also an essential prerequisite for effective transportation, communication, and other systems that provide access to international markets. At a local level, energy access facilitates development by enhancing the productivity of existing economic activities (e.g. enhancing agricultural development by enabling irrigation, value addition through crop processing, and storage) and helping rural areas to evolve from mere raw material producers to producers of value added products, while providing opportunities for new income and job-generating micro-enterprises (Oyedepo 2012.)

Development of a green industry (and the underlying infrastructure, work force, and value chains) presents an opportunity to increase access to affordable and sustainable energy that can both provide a sustainable source of jobs, income, and economic growth while also enabling growth in other sectors. Promotion of cost-effective RETs for productive uses in industry is therefore an integral component of sustainable development and presents a major opportunity for achieving the goals of ISID.

1.3. Industrial prosumers of renewable energy

The idea of generating energy for self-use as well as for sale to a grid is already quite common in larger industrial plants and companies in developed countries. However, the full spectrum of possibilities available to smaller-scale energy service providers – especially in terms of deployment of renewable energy in rural areas –require further promotion and the support of appropriate policies. Decentralized renewable energy systems have a good potential to become an important revenue stream for local enterprises. For example, modernizing the use of bio-energy in agro and forest industries can improve the efficiency of these operations, and benefit from auto-generation. Companies have the potential of integrating electricity or heat generation into their industrial activities. Bio-energy can be modernized through the application of advanced technology to convert raw biomass into electricity, liquid or gaseous fuels, or processed solid fuels, bringing significant social and economic benefits to both rural and urban areas.

The term “prosumers” emerged in the early 1980s to refer to individual consumers who also produced goods and services. While a few recent reports have focused on the potential of so-called “renewable energy prosumers” in the residential sector (Rickerson W., et al. 2014), very little attention has been given to the tremendous potential that exists to encourage the rise of renewable energy prosumers in the industrial sector.

Industrial prosumers of renewable energy are emerging as a central focus area of UNIDO’s renewable energy programme and an integral part of its strategy to achieve ISID. Types of industrial prosumers are numerous and can include, for example, pulp and paper mills, agro-industrial operations including pork, beef, and poultry farms, mining operations, abattoirs, manufacturing plants, solid waste management companies, or forestry-related facilities such as mills.

Box 1 | Industrial Prosumer Defined

‘Industrial Prosumer of Renewable Energy’: A Definition

An industry that produces and makes use of renewable energy sources such as solar, wind, bioenergy, etc. to supply a portion or all of its onsite energy needs. In many cases, this includes selling excess energy or electricity to the national/local grid or to the surrounding community.

In certain countries, prosumers of renewable electricity are also referred to as “embedded generators”, a term that underscores the fact that they remain connected to the main grid (Kukoyi, D. 2012). However, industrial prosumers are not limited to systems that are connected to a grid. In some cases, there is the potential for certain industrial operations to supply power directly to rural customers in an off-grid context, or even be incentivized to invest in mini-grid infrastructure themselves, turning formerly independent industrial prosumers into rural electrification providers. Such arrangements help support existing government efforts to increase rural electrification in off-grid and remote regions, and further accelerate the development of sustainable energy in the developing world.

Due to persistently high fossil fuel prices, and rapidly declining renewable energy generation costs, the business case for increasing the use of RETs in the industrial sector is becoming highly relevant. Diesel generation costs in most regions ranges from USD $0.30/kWh to over USD $2.00/kWh in remote regions, while the transport and use of fuel to these regions presents a host of environmental risks (e.g. fuel spillage, air quality, carbon emissions, etc.) as well as supply chain risks (bottlenecks, inadequate road infrastructure, etc.) Taken as a whole, these factors make the continued use of fossil fuels for power generation as well as for heating and cooling for industrial purposes increasingly unsustainable, and inconsistent with the increasing call toward a truly inclusive and sustainable industrialization. Fortunately, a new generation of technologies is now available to help substitute these various energy needs with more sustainable solutions.

With grid-connected renewable energy costs ranging from approximately USD $0.06/kWh to USD $0.20/kWh depending on the technology and location (See: http://costing.irena.org/media/2769/Overview_Renewable-Power-Generation-Costs-in-2012.pdf), there is now a wide range of available alternatives that can reduce, and potentially even replace, fossil fuel use in a number of industrial sectors. This can include the use of agricultural and forestry wastes for combined electricity and heat production (renewable CHP), as well as the use of waste energy resources at agro-industrial operations such as poultry, pork, beef, or dairy farms for biogas production. It could also include the direct use of wind power at industrial sites in certain regions, such as cement factories or manufacturing operations located along the coastline near major ports, where wind resources are generally stronger. There is also significant potential for the use of solar PV as well as solar CSP in many developing countries, whether to power local manufacturing and mining operations, or agricultural and livestock processing, and countless others.

In addition to renewable electricity, a number of cost-effective renewable thermal energy technologies are available which are ideally suited to application by businesses in the agro-industrial sector. In particular, waste-to-energy solutions (such as biomass gasification and anaerobic digestion) can make use of agricultural and animal waste products to generate clean-burning biogas or produce heat for industrial processes and space heating. Examples include gasification of rice husks, rice straw, and sugarcane bagasse; and anaerobic digestion of waste from cattle feedlots and chicken farms to create biogas. By repurposing waste streams, agro-industrial prosumers can have readily available and inexpensive (or free) materials while providing additional benefits to the community by reducing waste and the unsanitary or unpleasant conditions agro-industrial waste streams have been known to cause.

Disruptions in energy services are not uncommon in developing countries. Businesses in Sub-Sahara Africa (SSA) experience an average of eight 5-hour electrical outages per month, compared to just 1.6, one-hour outages experienced by firms in Eastern Europe and Central Asia (World Bank (2014). Disruptions in individual countries can be even more severe: between 2006 and 2009, the Republic of Congo, Guinea, Gambia, and Nigeria each report averaging at least 20 outages a month, each of which lasted an average of 6 hours or more. Such unstable supply of power can create significant financial hardships for businesses. Between 2006 and 2010, more than 50% of the Sub-Sahara African firms identified electricity as a major constraint to their businesses, compared to 27.8% of rest of the world that reported transportation as the most critical problem (World Bank (2012) Enterprise Survey Online Database). Losses due to electrical outages averaged about 7.4% of annual sales for businesses in the region, ranging as high as 25% for individual countries.

Common impacts of intermittent or unreliable power include lost productivity, disruption of services, and reduced employee and customer comfort. However, in certain industries impacts can be more severe: for example, even brief power disruptions in critical health care facilities could result in loss of life. Molten ore in an electronically heated oven can harden in 40 minutes, cause damage to the ovens, loss of material, and significant restart costs (Oseni, Musiliu O. (2012) Finally in the agro-industrial sector, prolonged power outages can cause refrigerated food to spoil, resulting in significant, direct losses of saleable goods. Estimates of financial impacts on businesses in SSA range from $0.46 and $1.25 per kWh of unsupplied electricity (Oseni, 2012.)

For these reasons, many businesses generate power on-site or install stand-alone back-up generators to mitigate the risks of power disruptions. The percentage of firms owning or sharing a back-up generator in Sub-Sahara African is 48.5%, the highest of any region in the world (World Bank, 2014) In some regions, this figure is over 80%, indicating a significant failure in the delivery of grid electricity (World Bank. 2014). Traditionally, backup power is provided by on-site diesel generators, the acquisition and operation of which represents a significant investment that could otherwise have been spent on more profitable business investments. Increasing access to renewable energy thus represents a significant opportunity for providing reliable, lower-cost, and sustainable energy source.

Small and medium-sized agro-industrial prosumers can also generate additional revenue by selling excess energy into the electricity grid or through other channels. Such prosumers thus act as rural energy entrepreneurs, supplying excess power to local communities while increasing rural access to electricity and renewable thermal energy for cooking and other domestic applications. Exporting excess generation from industrial energy producers to nearby residents can also offer additional synergies as most of businesses' energy demand occurs mid-day while household electricity use peaks in the evening during non-operating hours.

Part II
Bioenergy in developing countries

2.1. Biomass use and biomass potentials

Current biomass use on global scale is reported in table 1 below.

Table 1 | Traditional biomass and modern bioenergy flows in 2008 (IPCC-SRREN, 2011)

Type	Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Secondary Energy Carrier (EJ/yr)
Traditional Biomass Used for Bioenergy			
Accounted for in energy balance statistics	30.7	10-20	3–6
Estimated for informal sectors (e.g., charcoal)	6–12		0.6–2.4
Total Traditional Biomass Used for Energy	*37–43*		*3.6–8.4*
Modern Bioenergy			
Electricity and CHP from biomass, MSW and biogas	4.0	32	1.3
Heat in residential and public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road Transport Fuels (ethanol and biodiesel)	3.1	65	1.9
Total Modern Bioenergy	*11.3*	*59*	*6.6*

Notes: The global biomass supply of 50.3 EJ is composed of primary solid biomass (46.9 EJ), primary biogenic MSW used for heat and CHP (0.58 EJ); primary biogas for electricity and CHP (0.41 EJ) and for heating (0.33 EJ). Delivered ethanol, biodiesel, and other transport fuels (e.g., ethers) as secondary energy carriers made up 1.9 EJ. Examples of specific flows: output electricity from biomass 0.82 EJ (biomass power plants including pulp and paper industry surplus, biogas and MSW) and output heating from CHP was 0.44 EJ. Residential was calculated as total residential heat (33.7 EJ) minus the IEA traditional biomass used for energy estimate (30.7 EJ).

Biomass resource potentials and preconditions for sustainable deployment

Bioenergy production interacts with food, fodder and fibre production as well as with conventional forest products in complex ways. Bioenergy demand constitutes a benefit to conventional plant production in agriculture and forestry by offering new markets for biomass flows that earlier were considered to be waste products; it can also provide opportunities for cultivating new types of crops and integrating bioenergy production with food and forestry production to improve overall resource management. However, biomass for energy production can intensify competition for land, water and other production factors, and can result in overexploitation and degradation of resources. For example, too-intensive biomass extraction from the land can lead to soil degradation, and water diversion to energy plantations can impact downstream and regional ecological functions and economic services.

As a consequence, the magnitude of the biomass resource potential depends on the priority given to bioenergy products versus other products obtained from the land—notably food, fodder, fibre and conventional forest products such as sawn wood and paper—and on how much total biomass can be mobilized in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography), on agronomic and forestry practices, and on how societies understand and prioritize nature conservation and soil/water/biodiversity protection and on how production systems are shaped to reflect these priorities

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Literature studies range from zero (no biomass potential available as energy) to around 1,500 EJ, the theoretical potential for terrestrial biomass based on modelling studies exploring the widest potential ranges of favourable conditions (Smeets et al., 2007).

From a detailed assessment, the upper-bound technical potential of biomass was about 500 EJ with a minimum of about 50 EJ in the case that even residues had significant competition with other uses. The assessment of each contributing category performed by Dornburg et al. (2008, 2010) was based on literature up to 2007 (stacked bar of Figure 1) and is roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines (IPCC, 2000), assuming sustainability and policy frameworks to secure good governance of land use and major improvements in agricultural management. The resources used are:

- Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) were estimated at around 100 EJ/yr. This part of the technical potential biomass supply is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range.

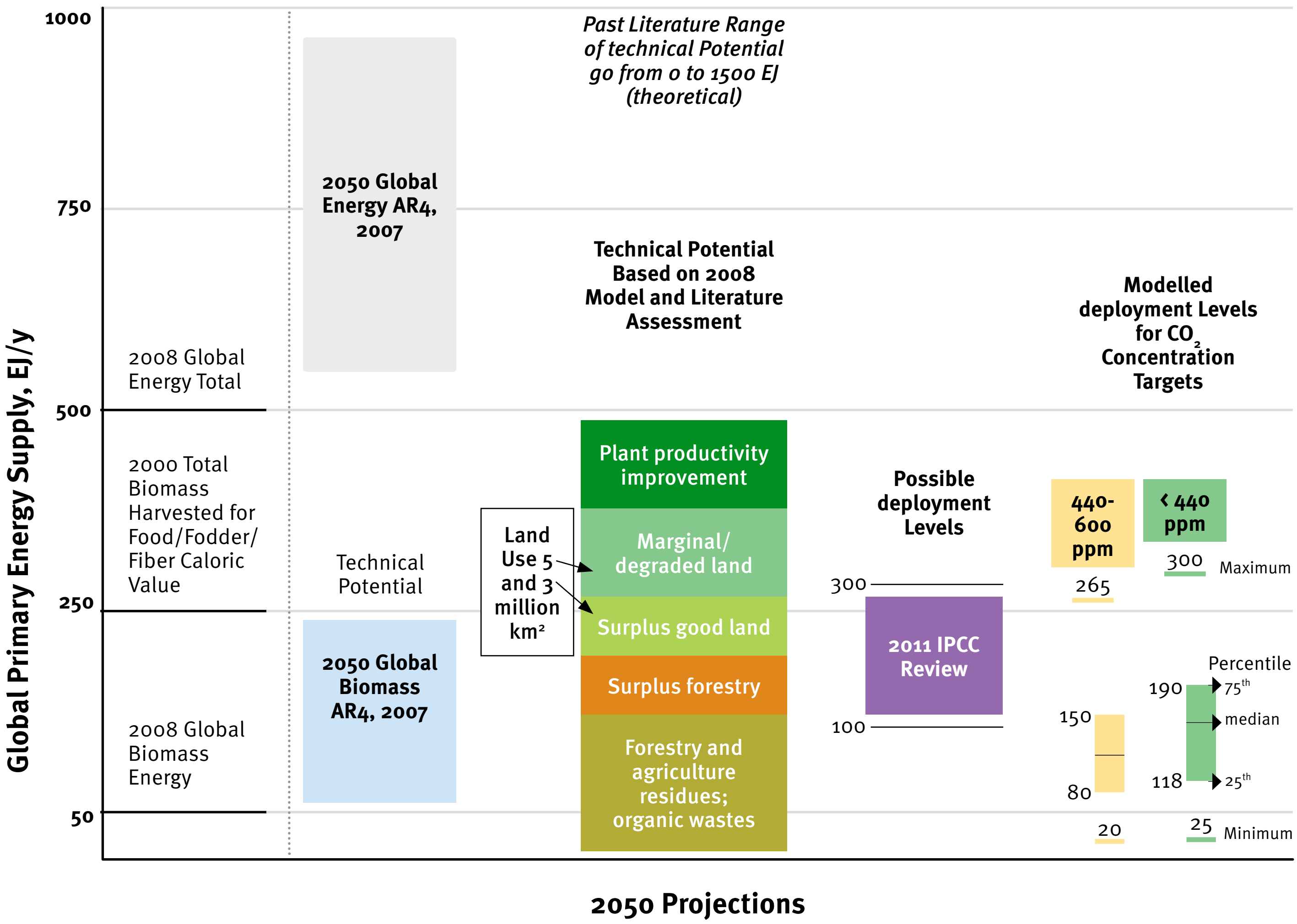
- Surplus forestry other than from forestry residues had an additional technical potential of about 60 to 100 EJ/yr.

- Biomass produced via cropping systems had a lower range estimate for energy crop production on possible surplus good quality agricultural and pasture lands of 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to an additional 70 EJ/yr, corresponding to a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology leading to improvements in agricultural and livestock management would add 140 EJ/yr.

Adding these categories together leads to a technical potential of up to about 500 EJ in 2050, with temporal data on the development of biomass potential ramping from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030 (Hoogwijk et al., 2005, 2009; Dornburg et al., 2008, 2010).

From the expert review of available scientific literature, *potential deployment levels of bioenergy by 2050 could be in the range of 100 to 300. EJ* Values in this range are described in van Vuuren et al. (2009), which focused on an intermediate development scenario within the SRES scenario family. The lower estimates of Smeets et al. (2007) and Hoogwijk et al. (2005, 2009) are in line with those figures. Important uncertainties in the given estimates include: population and economic/technology development; food, fodder and fibre demand (including diets); and development in agriculture and forestry, climate change impacts on future land use including its adaptation capability and the extent of land degradation, water scarcity, and biodiversity and nature conservation requirements.

Figure 3 | Global Primary Energy Supply

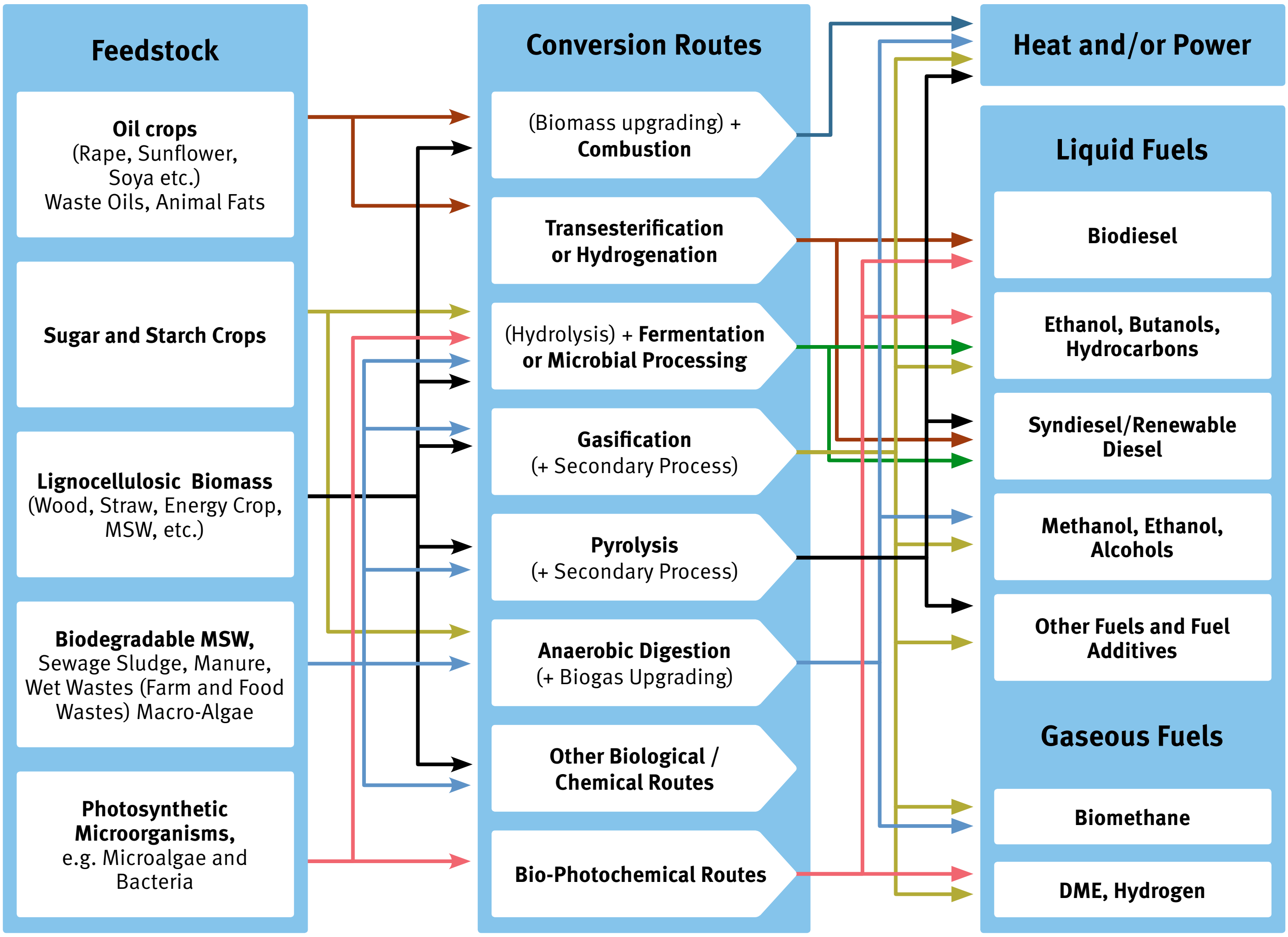


The above figure shows global projections of leading studies for primary energy supply up to 2050. On the left-hand side, the lines represent the 2008 global primary biomass supply for energy, the global primary energy supply, and the equivalent energy of the world's total harvest for food, fodder and fibre in 2000. A summary of major 2050 projections of global biomass primary energy supply is shown from left to right: (1) The IPCC AR4 report of 2007 estimates for global primary energy and technical potential for bioenergy; (2) upper bound of biomass technical potential based on integrated global assessment studies using five resource categories indicated on the stacked bar chart and limitations and criteria with respect to biodiversity protection, water limitations, and soil degradation, assuming policy frameworks that secure good governance of land use (Dornburg et al., 2010); (3) from the expert review of available scientific literature, potential deployment levels of bioenergy by 2050 could be in the range of 100 to 300 EJ; and (4) deployment levels of biomass for energy in two cases of climate mitigation levels (CO_2 concentrations by 2100 of 440 to 600 ppm (orange) or ‹440 ppm (green) bars or lines). Biomass deployment levels from model studies (4) are consistent with the expert review of potential deployment levels for bioenergy (3).The most likely range is 80 to 190 EJ/yr with upper levels in the range of 265 to 300 EJ/yr.

2.2. Biomass utilisation options and conversion technologies

Figure 4 depicts the main biomass conversion pathways, different key markets and energy carriers and in figure their development status is given.

Figure 4 | Schematic view of the variety of commercial and developing bioenergy routes from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels (modified from Bauen et al., 2009a).



Thermochemical processes

Biomass combustion is a process where carbon and hydrogen in the fuel react with excess oxygen to form CO_2 and water to release heat. Direct burning of biomass is popular in rural areas for cooking. Wood and charcoal are also used as a fuel in the industry. Combustion processes are well understood and a wide range of existing commercial technologies are tailored to the characteristics of the biomass and the scale of their applications. Biomass can also be co-combusted with coal in coal-fired plants.

Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen (anaerobic environment) that produces a solid (charcoal), a liquid (pyrolysis oil or bio-oil) and a gas product. The relative amounts of the three co-products depend on the operating temperature and the residence time allowed in the process. High heating rates of the biomass feedstocks at moderate temperatures (450°C to 550°C) result in oxygenated oils as the major products (70 to 80%), with the remainder split between a biochar and gases. Slow pyrolysis (also known as carbonization) is practiced throughout the world, for example, in traditional stoves in developing countries, in barbecues in Western countries, and in the Brazilian steel industry.

Table 2 | Examples of stages of development of bioenergy: thermochemical, biochemical, and chemical routes for heat, power, and liquid and gaseous fuels from solid lignocellulosic and wet waste biomass streams, sugars from sugarcane or starch crops, and vegetable oils (based on Bauen et al., 2009).

Plant	Type of Product	Stage of Development of Process for Product(s) or System(s)			
		Basic and Applied R&D	Demonstration	Early Commercial	Commercial
Low Moisture Lignocellulosic	Densified Biomass		Torrefaction Hydrothermal Oi (Hy Oil)l; Pyrolysis Oil (Py Oil)		Pelletization
Low Moisture Lignocellulosic	Charcoal		Pyrolysis (Biochar)		Carbonization
Low Moisture Lignocellulosic	Heat			Small Scale Gasification	Combustion Stoves
Low Moisture Lignocellulosic	Heat	Combustion			
Low Moisture Lignocellulosic	Heat			Py /Hy Oil	Home/District Industrial
Low Moisture Lignocellulosic	Power or CHP	Combustion coupled with			
Low Moisture Lignocellulosic	Power or CHP		Stirling Engine	ORC[1]	Steam Cycles
Low Moisture Lignocellulosic	Power or CHP	Co-Combustion or Co-firing with Coal			
Low Moisture Lignocellulosic	Power or CHP		Indirect	Parallel	Direct
Low Moisture Lignocellulosic	Power or CHP	Gasification (G) or Integrated Gasification (IG)			
Low Moisture Lignocellulosic	Power or CHP	IG-Fuel Cell IG-Gas Turbine		G and Steam Cycles	
Low Moisture Lignocellulosic	Power or CHP		IG-Combined Cycle		
Wet Waste	Heat or Power or Fuel	Anaerobic Digestion to Biogas			
Wet Waste	Heat or Power or Fuel		2-stage		Landfills (1-stage)
Wet Waste	Heat or Power or Fuel	Microbial Fuel Cells		Biogas Upgrading to Methane Reforming to Hydrogen	Small Manure Digesters
Wet Waste	Heat or Power or Fuel		Hydrothermal Processing to Oils or Gaseous Fuels		
Sugar	Fuels	Microbial Processing[2]		Sugar Fermentation	
Sugar	Fuels	Hydrogen	Gasoline/ diesel/jet fuel	Biobutanols[3]	Ethanol
Oils	Fuels			Hydrogenation	Extraction and Esterification
Oils	Fuels			Renewable diesel	Biodiesel

Notes: [1]ORC: Organic Rankine Cycle; [2]genetically engineered yeasts or bacteria to make, for instance, isobutanol (or hydrocarbons) developed either with tools of synthetic biology or through metabolic engineering. [3]Several four-carbon alcohols are possible and isobutanol is a key chemical building block for gasoline, diesel, kerosene and jet fuel and other products.

Biomass Gasification occurs when a partial oxidation of biomass happens upon heating. This produces a combustible gas mixture (called producer gas or fuel gas) rich in carbon monoxide and H_2 that has an energy content of 5 to 20 MJ/Nm^3 (depending on the type of biomass and whether gasification is conducted with air, oxygen or through indirect heating). This energy content is roughly 10 to 45% of the heating value of natural gas. Fuel gas can then be upgraded to a higher-quality gas mixture called biomass synthesis gas or syngas (Faaij, 2006). A gas turbine, a boiler or a steam turbine are options to employ unconverted gas fractions for electricity co-production. Coupled with electricity generators, syngas can be used as a fuel in place of diesel in suitably designed or adapted internal combustion engines. Most commonly available gasifiers use wood or woody biomass and specially designed gasifiers can convert non-woody biomass materials. Biomass gasifier stoves are also being used in many rural industries for heating and drying, for instance in India and China. Compared to combustion, gasification is more efficient, providing better controlled heating, higher efficiencies in power production and the possibility for co-producing chemicals and fuels.

Chemical processes

Transesterification is the process through which alcohols (often methanol) react in the presence of a catalyst (acid or base) with triglycerides contained in vegetable oils or animal fats to form an alkyl ester of fatty acids and a glycerine by-product. Vegetable oil is extracted from the seeds, usually with mechanical crushing or chemical solvents prior to transesterification. The fatty acid alkyl esters are typically referred to as 'biodiesel' and can be blended with petroleum-based diesel fuel. The protein-rich residue, also known as cake, is typically sold as animal feed or fertilizer, but may also be used to synthesize higher-value chemicals (WWI, 2006; Bauen et al., 2009).

The **hydrogenation** of vegetable oil, animal fats or recycled oils in the presence of a catalyst yields a renewable diesel fuel—hydrocarbons that can be blended in any proportion with petroleum-based diesel and propane as products. This process involves reacting vegetable oil or animal fats with hydrogen (typically sourced from an oil refinery) in the presence of a catalyst (Bauen et al., 2009a). Although at an earlier stage of development and deployment than transesterification, hydrogenation of vegetable oils and animal fats can still be considered a first-generation route as it is demonstrated at a commercial scale. Hydrogenated biofuels have a high cetane number, low sulphur content and high viscosity.

Biochemical processes

Biochemical processes use a variety of microorganisms to perform reactions under milder conditions and typically with greater specificity compared to thermochemical processes. These reactions can be part of the organisms' metabolic functions or they can be modified for a specific product through metabolic engineering (Alper and Stephanopoulos, 2009). For instance, *fermentation* is the process by which microorganisms such as yeasts metabolize sugars under low or no oxygen to produce ethanol. Among bacteria, the most commonly employed is *Escherichia (E.) coli*, often used to perform industrial synthesis of biochemical products, including ethanol, lactic acid and others. *Saccharomyces cerevisiae* is the most common yeast used for industrial ethanol production from sugars. The major raw feedstocks for biochemical conversion today are sugarcane, sweet sorghum, sugar beet and starch crops (such as corn, wheat or cassava) and the major commercial product from this process is ethanol, which is predominantly used as a gasoline substitute in light-duty transport.

Anaerobic digestion (AD) involves the breakdown of organic matter in agricultural feedstocks such as animal dung, human excreta, leafy plant materials, urban solid and liquid wastes, or food processing waste streams by a consortium of microorganisms in the absence of oxygen to produce biogas, a mixture of methane (50 to 70%) and CO_2. In this process, the organic fraction of the waste is segregated and fed into a closed container (biogas digester). In the digester, the segregated biomass undergoes biodegradation in the presence of methanogenic bacteria under anaerobic conditions, producing methane-rich biogas and effluent. The biogas can be used either for cooking and heating or for generating motive power or power through dual-fuel or gas engines, low-pressure gas turbines, or steam turbines. The biogas can also be upgraded through enrichment to a higher heat content biomethane (85 to 90% methane) gas and injected in the natural gas grid (Bauen et al., 2009a; Petersson and Wellinger, 2009). The residue from AD, after stabilization, can be used as an organic soil amendment or a fertilizer. The residue can be sold as manure depending upon the composition of the input waste.

Many developing countries, for example India and China, are making use of AD technology extensively in rural areas. Many German and Swedish companies are market leaders in large biogas plants (Faaij, 2006; Petersson and Wellinger, 2009). In Sweden, multiple wastes and manures (co-digestion) are also used and the biogas is upgraded to biomethane, a higher methane content gas, which can be distributed via natural gas pipelines and can also be used directly in vehicles.

2.3. Bioenergy systems and value chains: Existing state-of-the-art systems and their performance

The key commercial technologies are heat production (ranging from home cooking to district heating), power generation from biomass via combustion, CHP, co-firing of biomass and fossil fuels, and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol). Several bioenergy systems have been deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions and reached significant scales but still require government subsidies.

Modern bioenergy systems involve a wide range of feedstock types, residues from agriculture and forestry, various streams of organic waste, and dedicated crops or perennial systems. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production, and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20 TJ/km^2) for biofuel feedstocks, from 80 to 415 GJ/ha (8 to 41.5 TJ/km^2) for lignocellulosic feedstocks, and from 2 to 155 GJ/ha (0.2 to 15.5 TJ/km^2) for residues, while costs range from USD$_{2005}$ 0.9 to 16/GJ/ha (USD$_{2005}$ 0.09 to 1.6/TJ/km^2). Feedstock production competes with the forestry and food sectors, but the design of integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to 50% of the total costs of bioenergy production. Factors such as scale increases, technological innovation and increased competition have contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transport distances over 50 km. International costs of delivering densified feedstocks are sensitive to trade and are in the USD$_{2005}$ 10 to 20/GJ range for pellet fuels, and competitive with other market fuels in several regions, thus explaining why such markets are increasing. Charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns and densification technologies.

Bioenergy chains for power, combined heat and power, and heat

Unprocessed solid biomass is less costly than pre-processed types (via densification, e.g., delivered wood pellets at USD$_{2005}$ 10 to 20/GJ), but entails higher logistic costs and is a reason why both types of solid biomass markets developed. Because of economies of scale, some of the specific technologies that have proven successful at a large scale (such as combustion for electricity generation) are difficult to be directly applied to small-scale applications in a cost-effective fashion, making it necessary to identify suitable alternative technologies, usually adapting existing technologies used with carbonaceous fuels. This is the case for ORC technologies, which are entering the commercial stage, and Stirling engine technologies, which are still in developmental phase, or moving from combustion to gasification, coupled to an engine (IEA, 2008).

Many region-specific factors determine the production costs of bioenergy carriers, including land and labour costs, biomass distribution density, and seasonal variation. Also, other markets and applications partly determine the value of biomass. For many bioenergy systems, biomass supply costs represent a considerable proportion of total production costs. The scale of biofuel conversion technologies, local legislation and environmental standards can also differ considerably from country to country. Even the operation of conversion systems (e.g., load factor) varies, depending on, for example, climatic conditions (e.g., winter district heating) or crop harvesting cycles (e.g., sugarcane harvest cycles and climate impact). The result is a wide range of production costs that varies not only by technology and resource type, but also by numerous regional and local factors.

Many bioenergy chains employ cogeneration in their systems where the heat generated as a by-product of power generation is used as steam to meet process heating requirements, with an overall efficiency of 60% or even higher (over 90%) in some cases (IEA, 2008). Technologies available for high-temperature/high-pressure steam generation using bagasse as a fuel, for example, make it possible for sugar mills to operate at higher levels of energy efficiency and generate more electricity than what they require. Sugarcane bagasse and now increasingly sugarcane field residues from cane mechanical harvesting are used for process heat and power to such an extent that in 2009, 5% of Brazil's electricity was provided by bagasse cogeneration. Similarly, black liquor, an organic pulping product containing pulping chemicals, is produced in the paper and pulp industry and is being burnt efficiently in boilers to produce energy that is then used as process heat (Faaij, 2006). Cogeneration-based district heating in Nordic and European countries is also very popular.

A significant number of electricity generation routes are available, including co-combustion (co-firing) with non-biomass fuels, which is a relatively efficient use of solid biomass compared to direct combustion. Due to economies of scale, small-scale plants usually provide heat and electricity at a higher production cost than do larger systems, although that varies somewhat with location. Heat and power systems are available in a variety of sizes and with high efficiency. Biomass gasification currently provides an annual supply of about 1.4 GW_{th} in industrial applications, CHP and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane. At the smallest scales, the primary use of biomass is for lighting, heating and cooking.

Bioenergy production costs are specific to various settings, requiring data on biomass production and supply costs, consistent conversion methods, investment costs, land prices, and other factors, and often vary substantially from one region to the next.

Bioenergy value chains for liquid transport fuels

Bioenergy chains for liquid transportation fuels are similarly diverse and are described below under three subsections: (1) integrated ethanol, power, and sugar from sugarcane; (2) ethanol and fodder products; and (3) biodiesel. Also covered here are 2008 to 2009 biofuels production costs by feedstock and region. Though liquid biofuels are mainly used in the transport sector, in many developing and in some developed countries they are also used to generate electricity or peak power.

Integrated ethanol, power and sugar from sugarcane: Ethanol from sugarcane is primarily made from pressed juices and molasses or from by-products of sugar mills. The fermentation takes place in single-batch, fed-batch or continuous processes, the latter becoming widespread and being more efficient because yeasts can be recycled. The ethanol content in the fermented liquor is 7 to 10% in Brazil and is subsequently distilled to increase purity to about 93%. To be blended with gasoline in most applications, ethanol should be anhydrous and the mixture has to be further dehydrated to reach a grade of 99.8 to 99.9% (WWI, 2006).

Ethanol and fodder products: The dominant dry mill (or dry grind) process (88% of US production) for ethanol fuel manufactured from corn starts with hammer milling the whole grain into a coarse flour, which is cooked into a slurry, then hydrolyzed with alpha amylase enzymes to form dextrins, next hydrolyzed by gluco-amylases to form glucose that is finally fermented by yeasts (the last two processes can be combined). The byproduct is distillers' grains with solubles, an animal feed that can be sold wet to feedlots near the biorefinery or be dried for stabilization and sold. The most common source of process heat is natural gas.

Biodiesel: Biodiesel is produced from oil seed crops like rapeseed or soybeans, or from trees such as oil seed palms. It is also produced from a variety of greases and wastes from cooking oils or animal fats. This wide range of feedstocks, from low-cost wastes to more expensive vegetable oils, produces biodiesel fuels with more variable properties that follow those of the starting oil seed plant. Fuel standards' harmonization is still under development as are a variety of non-edible oil seed plants.

Another intermediate liquid fuel from pyrolysis is part of evolving heating and power in co-firing applications because it is a transportable fuel and is under investigation for stationary power and for upgrading to transport fuel.

Table 3 | Current and projected estimated production costs and efficiencies of bioenergy chains at various scales in world regions for power, heat, and biomethane from wastes directly taken from available literature data (IPCC-SRREN, 2011).

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/ biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US cents$_{2005}$/kWh	Potential Advances USD_{2005}/GJ US cents$_{2005}$/kWh
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Co-combustion with coal	5 to 100 MW_e, Eff. ~30 to 40%.[1,2] >50 power plants operated or carried on experimental operation using wood logs/residues, of which 16 are operational and using coal. More than 20 pulverized coal plants in operation.[3] Wood chips (straw) used in at least 5 (10) operating power plants in co-firing with coal.[3]	8.1 – 15 2.9 – 5.3 **Inv. Cost (USD/kW):** 100 – 1,300[1]	Reduce fuel cost by improved pretreatment, characterization and measurement methods.[4] Torrefied biomass is a solid uniform product with low moisture and high energy content and more suitable for cofiring in pulverized coal plant .[3] Cost reduction and corrosion-resistant materials for coal plant needed.[5]
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Direct combustion	10 to 100 MW_e, Eff. ~20 to 40%.[1,2] Well deployed in Scandinavia and North America; various advanced concepts give high efficiency, low costs and high flexibility.[2] Major variable is biomass supply costs.[2]	20 – 25 7.2 – 9.2 **Inv. Cost (USD/kW):** 1,600 – 2,500[1]	U.S. 2020 cost projections:[6] 6.3 – 7.8 Stoker fired boilers: 7.5 – 8.1
MSW/ Worldwide	Direct combustion (gasification/ co-combustion with coal	50 to 400 MW_e, Eff. ~22%, due to low-temperature steam to avoid corrosion.[7,8] Commercially deployed incineration has higher capital costs and lower (average) efficiency.[2] Four coal-based plants co-fire MSW.[3]	9.1 – 26 3.3 – 9.4[7]	New CHP plant designs using MSW are expected to reach 28 to 30% electrical efficiency, and above 85 to 90% overall efficiency in CHP.[8]
Wood/ Ag. Wastes/ Worldwide	Small scale/ gas engine gasification	5 to 10 MW_e, Eff. ~15 to 30%.[1,2] First-generation concepts prove capital intensive.[2]	29 – 38 10 – 14 **Inv. Cost (USD/kW):** 2,500 – 5,600[1]	Increased efficiency of the gasification and performance of the integrated system. Decrease tars and emissions.[1]
Wood pellets/ EU	Direct coal co-firing or co- gasification	12.5 to 300 MW_e.[9] Used in 2 operating power plants in co-firing with coal.[3] Costs highly dependent on shipment size and distances.[9]	14 – 36 5.0 – 13[9,10]	See PELLETS@LAS Pellet Handbook and www.pelletsatlas.info
Pyrolysis oil /EU	Coal co-combustion/ gasification	12.5 to 1,200 MW_e.[9] Costs highly dependent on shipment size and distances.[9]	19 – 42 7.0 – 15[9,10]	Develop direct conventional oil refinery integrated and/or upgrading processes allowing for direct use in diesel blends.[1]

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/ biomass energy Component costs in USD_{2005}/GJ	Estimated Production Cost USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Fuelwood/ Mostly in developing countries	Combustion for heat	0.005 to 0.05 MW_{th}, Eff. ~10 to 20%.[2] Traditional devices are inefficient and generate indoor pollution. Improved cook stoves are available that reduce fuel use (up to 60%) and cut 70% of indoor pollution. Residential use (cooking) application.[2]	**Inv. Cost (USD/kW):** 100[2]	New stoves with 35 to 50% efficiency also reduce indoor air pollution more than 90%.[2] See Section 2.5.7.2.
		1 to 5 MW_{th}, Eff. ~70 to 90% for modern furnaces.[2] Existing industries have highly polluting low-efficiency kilns.[11]	**Inv. Cost (USD/kW):** 300 – 800[2]	More widespread use of improved kilns to cut consumption by 50 to 60% and reduce pollution.[11]
Organic Waste/ MSW/ Worldwide	Landfill with methane recovery	Eff. ~10 to 15% (electricity).[2] Widely applied for electricity and part of waste treatment policies of many countries.[2]	**Biogas:** 1.3 – 1.7[12]	Continued efficiency increases are expected.
Organic Waste/ MSW/ Manures/ Sweden/ EU in expansion	Anaerobic co-digestion, gas clean up, compression, and distribution	Widely applied for homogeneous wet organic waste streams and waste water.[2] To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes.[2]	**Fuel:** 2.4 – 6.6[13] **Elec.:** 48 – 59[1] 17 – 21[1]	Improvements in biomass pretreatment, the biogas cleansing processes, the thermophilic process, and biological digestion (already at R&D stage).[1, 17]
		Costs do not include credits for sale of fertilizer byproduct.[14]	**Fuel:** 15 – 16 **Inv. Cost (USD/kW):** 13,000[14]	In commercial use in Sweden, other EU countries. State of California study shows potential for the augmentation of natural gas distribution.[14]
Manures/ Worldwide	Household digestion	Cooking, heating and electricity applications. By- product liquid fertilizer credit possible.	1 to 2 years payback time	Large reductions in costs by using geomembranes. Improved designs and reduction in digestion times.[15]
Manures/ Finland	Farms	Biogas from farms 0.018 to 0.050 MW_e.[16]	**Elec.:** 77 – 110 **Inv. Cost (USD/kW):** 14000 – 23000[16]	Improved designs and reduction in digestion times. Improvements in the understanding of anaerobic digestion, metagenomics of complex consortia of microorganisms.[12]
Manures/ Food residues	Farms/Food Industry	Biogas from farm animal residues and food processing residues at 0.15 to 0.29 MW_e.[16]	**Elec.:** 70 – 89 **Inv. Cost (USD/kW):** 12000 – 15000[16]	

Abbreviations: Inv. = Investment; Elec. = Electricity.

References:1Bauen et al. (2009a); 2IEA Bioenergy (2007); 3Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 4Econ Poyry (2008); 5Egsgaard et al. (2009); 6National Research Council (2009b); 7Koukouzas et al. (2008); 8IEA (2008a); 9Hamelinck (2004); 10Uslu et al. (2008); 11REN21 (2007); 12Cirne et al. (2007); 13Sustainable Transport Solutions (2006); 14Krich et al. (2005); 15Müller, (2007); 16Kuuva and Ruska (2009); 17Petersson and Wellinger, 2009.

Future cost trends for pre-commercial bioenergy systems

A number of bioenergy systems are evolving, as shown in Figure 4. The key intermediates that enable generation of modern secondary bioenergy include syngas, sugars, vegetable oils/lipids, thermochemical oils derived from biomass (pyrolysis or other thermal treatments), and biogas. These intermediates can produce higher efficiency electricity and heat, a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, and chemical products and polymers (bio-based materials) in the developing biorefineries. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covering the range of gasoline, diesel and higher-energy transport fuels such as jet fuels and chemicals. Both improved first-generation crops, perennial sugarcane-derived, in particular, and second-generation plants have the potential to provide a variety of energy products suited to specific geographic regions, and high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.

Table 4 presents projected production costs for developing technologies such as integrated gasification combined cycle for the production of higher efficiency electricity and gasification- (syngas) derived fuels, including diesel, jet fuel, and hydrogen, methane, dimethyl ether and other oxygenated fuels through catalytic upgrading of the syngas. The sugar intermediates, lignocellulosic for instance, can be converted through biochemical routes to a variety of fuels with the properties of petroleum-based fuels. Similarly, pyrolysis oil-based hydrocarbon fuels are under development. Oilseed crop and tree seed oil development could also expand the range of fuel products with properties of petroleum fuels because they are readily upgraded to hydrocarbons. Finally, algae for biomass production are photosynthetic, using CO_2, water, and sunlight to biologically produce a variety of carbohydrates, lipids, plastics, chemicals or fuels like hydrogen, along with oxygen. In addition, heterotrophic microbes, such as certain algae are engineered to metabolize sugars and excrete lipids in the dark. Microorganisms or their consortia can consolidate various processing steps; genetically engineered yeasts or bacteria can make specific fuel products, including hydrocarbons and lipids, developed either with tools from synthetic biology or through metabolic engineering.

Table 4 | Projected production costs estimated for developing technologies.

Select Bioenergy Technology	Energy Sector (Electricity, Thermal, Transport)*	2020–2030 Projected Production Costs (USD_{2005}/GJ)
IGCC[1]	Electricity and/or Transport	12.8–19.1 (4.6–6.9 US cents/kWh)
Renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]		12–25
Lignocellulose pyrolysis-based biofuels[4]		14–24 (blendstock)
Gaseous biofuels[5]	Thermal and Transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: [1]Feed cost USD 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate; [2]ethanol, butanols, microbial hydrocarbons and microbial hydrocarbons from sugar or starch crops; [3]syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol; [4]biomass pyrolysis (or other thermal treatment) and catalytic upgrading to gasoline and diesel blendstocks or to jet fuels; [5]synfuel to SNG, methane, dimethyl ether, or hydrogen from biomass thermochemical and anaerobic digestion (larger scale). * Many routes could be coupled with CCS when these technologies are mature and thus provide negative emissions.

2.4. Impacts of biomass utilisation and potential contribution to sustainable development

Increased demand for agricultural and forestry waste materials (i.e. residues) can supplement farmers' and foresters' incomes, particularly if the wastes were previously burned or landfilled. Bioenergy can also generate jobs; in general, bioenergy generates more jobs per unit of energy delivered than other energy sources, largely due to feedstock production, especially in developing countries and rural areas (FAO, 2010b).

Wage income is a key contribution to the livelihoods of many poor rural dwellers. The benefits from bioenergy jobs depend on the relative labour intensity of the feedstock crop compared to the crop that was previously grown on the same land. For example, cultivation of perennial energy crops requires less labour than cereal crop cultivation, and this displacement effect should be taken into account. While increased employment is an important potential benefit, highly labour-intensive operations might also reduce competitiveness (depending on the relative prices of labour and capital).

The number of jobs created is very location-specific and varies considerably with plant size, the degree of feedstock production mechanization and the contribution of imports to meeting demand. Estimates of the employment creation potential of bioenergy options differ substantially, but liquid biofuels based on traditional agricultural crops seem to provide the most employment, especially when the biofuel conversion plants are small (Berndes and Hansson, 2007). Even within liquid biofuel options, the use of different crops introduces wide differences. For ethanol, the number of direct and indirect jobs generated ranges from 45 (corn) to 2,200 (sugarcane) jobs/PJ of ethanol. For biodiesel, the number of direct and indirect jobs generated ranges from 100 (soybean) to 2,000 (oil palm) jobs/PJ of biodiesel. For electricity production, mid-scale power plants in developing countries using a low-mechanized system (25 MW) are estimated to generate approximately 400 jobs/plant or 250 jobs/PJ, of which 94% are in the production and harvesting of feedstocks. For instance, in a detailed UK study, 1.27 jobs/GWh were calculated for power from a 25 MWe plant using dedicated crops (woody or *Miscanthus*). During the complete life cycle 4000 - 6000 person-year jobs are created, representing on an yearly basis 200 jobs/PJ (15, 73, and 12% at the electricity plant, feedstock production and delivery, and induced, respectively)(Thornley et al., 2008).

Impacts on rural and social development

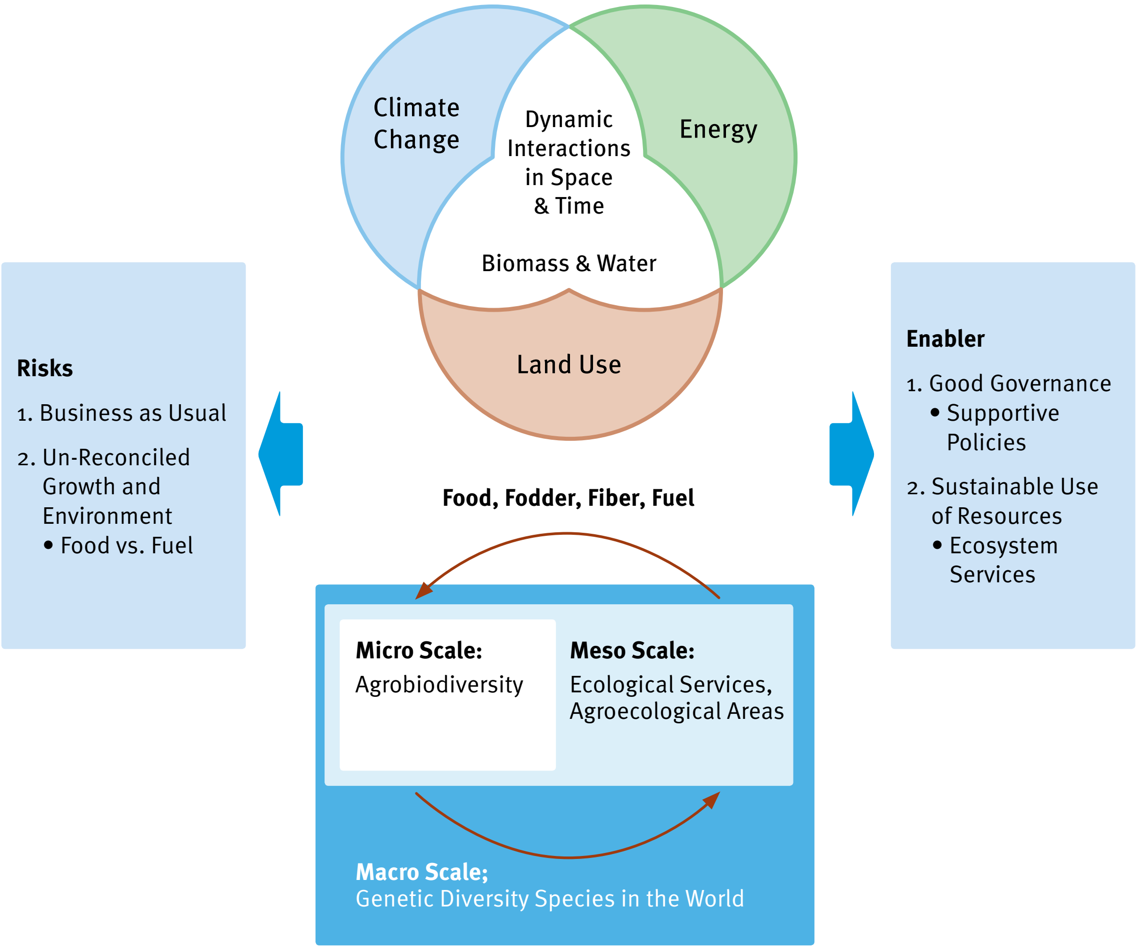
Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries. The development potential critically depends on whether the bioenergy market is economically sustainable without government subsidies. If long-term subsidies are required, fewer government funds will be available for the wide range of other public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Experience from Latin America shows that governments that use agricultural budgets for investment in public goods instead of subsidies experience faster growth, more rapid poverty alleviation and less environmental degradation.

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security This contribution could be substantial for countries with large amounts of arable land per person (FAO, 2008a). Recent analyses of the use of indigenous resources implies that much of the expenditure on energy is retained locally and recirculated within the local or regional economy, but there are trade-offs to consider. For example, the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause a temporary lack of biomass supply during periods of high demand. Households could be particularly vulnerable to this market distortion.

The biofuels production technologies and institutions will also be an important determinant of rural development outcomes. In some instances, private investors will look to establish biofuel plantations to ensure security of supply. If plantations are established on non-productive land without harming the environment, there should be benefits to the economy. It is essential not to overlook the uses of land that are important to the poor. Governments may need to establish clear criteria for determining whether land is marginal or productive, and these criteria must protect vulnerable communities and female farmers who may have less secure land rights (FAO, 2008a). Research in Mozambique shows that, compared with a more capital-intensive plantation approach, an out-grower approach to producing biofuels helps to reduce poverty due to the greater use of unskilled labour and accrual of land rents to smallholders (Arndt et al., 2010).

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply side economic response, the negative effects of higher food prices will predominate. If higher prices motivate greater public and private investment in agriculture (e.g., rural roads and education, R&D), there is tremendous potential for sparking medium- and long-term rural development. As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6% and reduce the incidence of poverty by about 6% over a 12-year period between 2003 and 2015 (Arndt et al., 2010).

Figure 5 | Bioenergy's complex, dynamic interactions among society, energy and the environment include climate change feedbacks, biomass production and land use with direct and indirect impacts at various spatial and temporal scales on all resource uses for food, fodder, fibre and energy. Biomass resources must be produced in a sustainable way as their impacts can be felt from micro to macro scales. Risks are maintenance of business-as-usual approaches with uncoordinated production of food and fuel. Opportunities are many and include good governance and sustainability frameworks that generate strong policies that also lead to sustainable ecosystem services (van Dam et al., 2010).



In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources do, about 200 to 2000 jobs/PJ. Also when the intensification of conventional agriculture would free up land that could be used for bioenergy, the total job impact and added value generated in rural regions increases when bioenergy production increases. Effective pasture/agriculture land use management could increase the rainfed potential significantly. For many developing countries, the potential of bioenergy to generate employment, economic activity in rural areas, and fuel supply security are key drivers. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed.

The bioenergy options that are developed, the way they are developed, and under what conditions will have a profound influence on whether impacts will largely be positive or negative. The development of standards or criteria (and continuous improvement processes) can push bioenergy production to lower or positive impacts and higher efficiency than existing systems. Bioenergy has the opportunity to contribute to climate change mitigation, energy security and diversity goals, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

Part III
Biomass gasification

Gasification as a means to convert a diversity of solid fuels to combustible gas or syngas received considerable attention in recent years. Gasification converts biomass into fuel gas, which can be further converted or cleaned prior to combustion (e.g. in a gas turbine; when integrated with a combined cycle this leads to a BIG/CC Biomass Integrated Gasification/Combined Cycle plant).

In this section we will first focus on production of heat and power deploying biomass gasification. We will distinguish between smaller scale gasification (i.e. in the 10's of kWth to around 1 MWth capacity range and generally involving fixed bed gasification concepts) and larger scale gasification, generally linked to Fluid Bed concepts.

3.1. Small scale gasification

Since the end 80's and beginning of the90's, small-scale gasification received major support. Downdraft or updraft, fixed bed gasifiers with capacities of less than a 100 kWth up to a few MWth were developed and tested for small-scale power and heat generation using diesel or gas engines. Heat production using small gasifiers is commercially established. Finland in particular was successful in the 80's in deploying smaller scale (Bioneer) gasifiers for heat production. Nevertheless, gasification for production of heat finds a strong competitor in combustion. A key concept pursued for a long period of time was the use of agricultural residues close to its source, thus minimizing transport distances. A wide array of concepts for gasifiers, gas cleaning and system integration for such concepts was proposed and tested in a wide variety of conditions. Technology was also exported to many developing countries with support from international bodies such as the World Bank. The key drivers here were rural development and electrification.

The gasification technology is principally well suited for small power plants. Appropriate gasifier systems with internal combustion engines can produce 1 kWh of electricity from 1.1 – 1.5 kg wood, 0.7 – 1.3 kg charcoal, or 1.8 – 3.6 kg rice husks. Assuming the wood originates from renewable production – regardless of whether planned forestation or natural regeneration - it would be a perfect, nearly CO2 neutral, renewable energy source. Hence, this technology is a very interesting solution for many initiatives and projects that look into CO_2 emissions reduction. The general features of the technology are indeed promising: in contrast to a photovoltaic system or a wind generator, electricity can be produced at any desired time given the availability of the required biomass. A generator in the range between 10 and 100 kW provide electricity for televisions, refrigerators and the operation of small machinery for productinve use. In addition, the provision of fuel in the form of wooden sticks or agricultural waste can be a source of income for small farmers and an incentive for reforestation. However, documentation of practical experience shows that there are still some obstacles to overcome to adapt the technology to the needs and capacities of the rural population in developing countries (Dimpl, GTZ, 2010).

In countries such as India and Sri Lanka gasification technology is used quite frequently and installation companies have an active communication strategy. In fact, one of the most encouraging reports comes from Saran Renewable Energy Pvt Ltd which received the 2009 Ashden Award for replacing diesel generators with biomass gasification systems. According to reports, a gasification plant with a dual fuel generator supplies up to 128 kW of electricity to small businesses, farms and households in Bihar through a local grid spanning about 1.5 km. The plant costs were US$170,000, about 90% of which was spent on the gasifier and generator and about 10% on the distribution line. About 30% of the plant was subsidized by the government. US$0.04/kg is paid to local farmers for supplying biomass, mainly stems of a locally grown tree named 'dhaincha', probably a Sesbania plant. In addition, 10-15% diesel fuel is co-fired to ensure proper ignition. Customers are charged about US$0.15/kWh.

With this tariff structure the plant is expected to recover the capital costs within 6 years. A crucial factor for the economically successful operation of this plant seems to be the dense cluster of small business customers (grain mills, cold stores, sawmill, welding workshop and farmers). Most of them use diesel generators to drive the machinery of their irrigation pumps and thus replace high costs for electricity. The introduction of the gasifier plant is reported to have resulted in about 40% lower costs.

One of the most important manufacturers is an Indian Company based in Gujarat. The company confirms having installed hundreds of gasifiers for small power plants of 3 – 500 kW all over the world, e.g. in Austria, Uganda, Madagascar, India, Bangladesh and Australia. The plants are fired with wood and agricultural residues. However many of the gasifiers are used in small industries for combustion and heating purposes only.

In Sri Lanka,a recent, as yet unpublished study reports on a gasification project that has already been working well for more than one year. The 12 kW plant provides electricity for 27 families, considerably reducing their consumption of kerosene. On average each family saves about EUR 0.80/month. The families pay a monthly fee of EUR 1.25 and contribute 60 kg of dry chopped wood as fuel. But this is just enough to cover the running costs. The initial investment costs were covered by the project. However, given the small size of the plants, the operation of the plant is laborious and requires a committed, permanently employed operator. Every day the filters have to be cleaned and once a month the whole plant has to be disassembled and cleaned of tar and soot. Furthermore, compared to other renewable energy technologies gasification proved to be expensive. The per capita investment costs for the gasification power plant were about 30-40% higher than those for a micro-hydro power plant or solar home systems installed in the region. Obviously the running costs are considerably higher as well (Laufer, 2009).

Box 2 |

Husk Power Systems: Electricity from Rice Husks in Bihar's Villages (India)[1]

Husk Power Systems (HPS) provides electricity to around 100,000 people across 125 villages in India, using biomass gasifiers fuelled by rice husks. Rice husk is compressed to bricks. At the end of the process some char is produced in addition to the fuel gas. Fuel gas is cleaned by four filters, and then it is used to fuel an internal combustion engine and generate electricity. A mini-grid system transmits the electricity to the houses in a range of 3 km. HPS business model is primarily focused on villages that are off-grid. At the moment, there are 35 power plants in operation with a generation capacity in the range 32–52 kW. A 32 kW plant needs 50 kg of fuel per hour, and power about 700 typical rural households. Customers pay in advance for electricity, and the cost is less than they might have previously paid for diesel or kerosene.

Key aspects of this case study:

- Source of energy: rice husk. 50 kg of rice husk an hour can run a 32 kW plant. Thus 1.8 billion kg of rice husk (Biharos 1 year production) could produce about 2.2 GW of power
- Supply chain: husk purchased from local rice mills. One month's stock of husk ensures dry feed during the monsoon.
- Funding: initial investments come from personal funds. HPS has also received support from some international funding bodies and from Indian Ministry of New and Renewable Energy.
- Investment: total installation costs are less than $1/watt, including distribution. Running costs are about $350, including salaries, husk cost, maintenance cost.
- Return time: about 2–3 months to become operationally profitable, and 2–3 years for capital expenditure to be returned, depending on subsidies.
- End users: 11,000–12,000 connections have been taken across over 125 villages, of which 80–90 % are domestic users.
- Billing and payment: domestic users pay about $1.5 per month for a 30 W connection. Electricity is available for 6–7 h in the evening in most sites.

1 Boyle G (2010) Empowering Bihar: case studies for bridging the energy deficit and driving the change. Greenpeace India Society. Bengaluru, India, P.24

3.2. Overall appraisal of the potentials and challenges of smallgasifiers

Even though availability of operation data is limited, the multitude of gasification projects allows for an appraisal of their potentials and challenges for developing countries:

- Gasification technology is principally well suited for small power plants. Producer gas can be used as fuel for both Otto (gasoline) engines and diesel engines. In general these engines have to be adapted slightly to this fuel. Otto engines can run exclusively on producer gas while diesel engines need admixing with conventional diesel fuel.

- The investment costs for a gasification plant vary significantly. Data from Sri Lanka to European countries range from EUR 150/kWe to EUR 3,000/kWe. It is likely that the cheap gasifiers from local production require more maintenance and that these costs are often not quantified.

- The technology is modular and labour intensive which fits the conditions of several developing countries.

- The technology is still at an early commercial stage, many gasifier plants undergo a prolongued test period after installation.

- Appropriate fuel is dry chopped wood, charcoal and, with appropriate equipment, rice husk. The use of other raw materials for fuel like peanut shells, straw etc. has not been resolved as yet and could require co-firing of considerable amounts of other (fossil) fuel.

- Specific fuel consumption of gasifier systems with internal combustion engines depends on the type of raw fuel and ranges between 1.1 – 1.5 kg/kWh for wood and between 1.8 and 3.6 kg/kWh for rice husk gasifiers.

- Wood fuel gasification systems in combination with Otto engines show overall system efficiencies (energy in the fuel/electrical energy produced) from 16 to 19 per cent. Gasification systems fuelled by rice husk show overall efficiencies of 7 to 14 per cent. By integrating gasifiers in combined heat and power systems (CHP) their efficiencies can approach 80%.

- Clean operation of downdraft reactors can only be achieved in a small power range. Hence, steady full load operation of the plants with maximum turn down ratios of about 50% of full load is crucial for efficient operation and achieving tar-free gas production.

- The economic benefits of small-scale power gasifiers depend on the potential savings of switching from high-cost commercial fuel to locally available low-cost biomass. The potential fuel cost savings have to compensate the higher costs for the initial investment, labour, operation and maintenance.

- Limited reliable operating data on the economy of gasification plants is available.

- There remains the main technical challenge of achieving a high purity of the producer gas to avoid the formation and accumulation of tar and soot. The internal combustion engines have strict purity requirements regarding the generator gas. Too much particular matter, tar or other residues decrease the lifetime of the combustion engine and make frequent maintenance necessary.

- The main strategy to address this challenge is to equip gasifier systems with a gas filter. This raises the costs, requires frequent cleaning of the filter system, and often produces much carcinogenic waste, especially in the case of wet stripping of the gas.

- The remaining ashes are unproblematic and can be used as fertiliser, e.g. in fuel wood plantations.

- The gaseous emissions of a well-established and well-operated gasification plant are low. The gas is used as fuel for the combustion motor and its exhaust gases are similar to those of engines running on fossil fuels. If originating from renewable sources they contribute significantly to reducing the GHG burden.

- Small (fixed bed) gasifiers coupled to diesel/gas engines (typically for 100 - 200 kWe systems with an approximate, modest, electrical efficiency of 15-25%) are commercially available on the market. Especially in India, succesful implementation has been achieved. However, the critical demands of small-scale gasifiers as regards fuel quality (preferably standardized and hence more expensive fuel such as pellets) and careful operation along with high costs, especially for effective gas cleaning given the severe emission standards, have so far hampered their wide deployment in the EU. Possibly, in the longer term, standardized gasification systems ('pre-packaged') using fuel cells and micro-turbines could mean a breakthrough for small scale electricity production from biomass, but such systems need further development and will depend on cheap and reliable fuel cells and again, major advances in small scale gas cleaning.

Therefore, at present the application of the gasifier technology for small-scale electricity production in developing countries should overcome some preconditions:
- High and constant availability of cheap appropriate biomass fuel;
- Availability of specialised know-how for maintenance and operation;
- Availability of an experienced manufacturer/service provider;
- Low labour costs;
- Sufficient economic potential of the electricity users to cover at least the operational costs.

Additional conducive conditions would be:
- Besides electricity use, heat or other by-products of the system can be sold or used in a profitable way.
- Positive side effects such as providing an incentive for reforestation, reducing GHG emissions etc. justify considerable subsidies.
- Initial capital does not have to be repaid directly by the consumer of the electricity produced; subsidies are in place.

3.3. Large scale (CFB) biomass gasification

Larger gasifiers (i.e. over several 10's MWth capacity are generally associated with Circulating Fluidized Bed concepts which have high fuel flexibility. At atmospheric pressure (ACFB) gasifiers are used for production of (raw) producer gas and process heat (e.g. in Italy, Austria, Sweden and Germany) but not in very large numbers. Biomass Integrated Gasification/Combined Cycle (BIG/CC) systems combine flexibility with respect to fuel characteristics with a high electrical efficiency. Electrical efficiencies around 40% (LHV basis) are possible on a scale of about 30 MWe on shorter term, [Faaij et al. 1997]. BIG/CC became the centre of attention in EU and various national programs in the first half of the nineties.

The promise of this technology, allowing for high electrical efficiency at modest scales combined with modest capital costs, resulted in a variety of research and demonstration initiatives. Furthermore, BIG/CC concepts can achieved low emission to air levels, because the fuel gas needs severe cleaning prior to combustion to meet gas turbine specifications [Faaij et al,, 1997]. Cover the past decades, the realization of the demonstration projects proved to be difficult. Costs of first generation units proved to be very high. The first generation of BIG/CC systems shows high unit capital costs. Depending on the scale, price levels of 5,000-3,500 Euro/kWe are quoted [Faaij et al., 1998], which is still far from the desired 1,500-2,000 Euro/kWe, which could bring BIG/CC in a competitive area. Various technological issues (e.g. concerning pre-treatment and tar removal) still need to be resolved. Later in the nineties, many utilities faced rapid market liberalization in the energy sector and expensive demonstration activities proved to be hard to pursue. Various demonstration units (such as ARBRE and BIOFLOW) were put out of operation recently. Co-firing and proven combustion technology (which also develops over time) is generally favoured by the risk-averse energy sector. This has led to the deplorable situation of stalled development of a technology that, on a somewhat longer term, is capable of producing power from biomass at competitive price levels. At somewhat larger scale (over 100 MWe) and considering the ongoing improvement of gas turbine technology, the cost reduction potential of BIG/CC systems is considerable, as has been evaluated by numerous studies, [Faaij et al. 1998]. The combination of high electrical efficiencies with relatively low unit capital costs can make the use of cultivated biomass as feedstock economically feasible for many areas in the world. So far, however, development is slow.

3.4. Gasification for co-firing

Gasification is also a route towards large co-firing shares of existing (coal-fired) power plants, avoiding the need for additional solid fuel feeding lines and allowing for better control of the combustion process. Successful deployment of (A) CFB gasifiers is recently shown in co-firing schemes (e.g. Lahti in Finland and Amer in the Netherlands). An interesting alternative application for producer gas from biomass gasification is to use it for co-firing in existing (or new) natural gas fired combined cycles. In this way, economies of scale are utilised resulting at in low cost and (very) high overall efficiencies (currently up to 60% for NG fired combined cycles), combined with a secure fuel supply since one can vary the share of fuel gas and natural gas fired. So far, this option has not been demonstrated anywhere in the world, but research efforts are increasing and it could prove to be of major importance on short term given that co-firing opportunities at existing coal-fired power plants are increasingly utilised already.

Gasification of biomass to syngas (CO and H_2) followed by catalytic upgrading to either ethanol or butanols has estimated production costs (USD_{2005} 12 to 20/GJ) comparable to the biochemical chains discussed above. The lowest-cost liquid fuel is methanol (produced in combination with power) at USD_{2005} 7 to 10/GJ (USD_{2005} 12 to 18/GJ for fuel only). Further reduction in production costs of fuels derived from gasification will depend on significant development of IGCC (currently at the 5 to 10 MW_e demonstration phase) to garner practical

Table 5 | Gaseous Fuels, Power and Heat from Gasification

Process	Feedstock	Efficiency and process economics Eff. = product energy/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification/ syngas processing of hydrogen to fuel and power	Ligno-cellulosic	Eff. 60% (fuel only). Needs 0.19 GJ_e/GJ H_2 for liquid estimated at USD 11–14/GJ (long term), wood USD 2.4/ GJ, USD 568/kW_{th} capital.[19]	88[30]	Co-production H_2 and power (55% fuel efficiency, 5% power) in the longer term.[19] USD 426/kW_{th} capital[19]	4–5[19] (longer) 6[20]–12[12] 5.5–7.7[41]	R&D stage
Gasification/ methanation to methane for fuel, heat and/or power	Ligno-cellulosic	Eff. ~60% (or higher for dry feed).[42] Combined fuel and power production possible.	98[27]	RD&D on gas clean up and methanation catalysts. For wet feedstocks wet gasification developing[46]	10.6–11.5[42] wood USD 2.8/GJ	RD&D stage; commercial in Austria
Anaerobic digestion, upgrading of gas, liquefaction	Organic wastes, sludges	Eff. ~20 to 30%; includes mixtures of animal and agriculture residues		Improve technology robustness with new metagenomic tools, reduce costs	15–16[21]	
Integrated gasification combined cycle for CHP	Ligno-cellulosic	District heating; power-to-heat ratio 0.8 to 1.2; power production efficiency 40 to 45%; total efficiency 85 to 90%. Investment USD 1,200/kWh_{th}. Wood residues in Finland[22]	96[31]	Gas cleaning, increased efficiency cycles, cost reductions.	8–11[11]	Demos at 5 to 10 MW projected cost at USD 29–38/GJ or US cents 10–13.5/ kWh[45]
				IGCC at 30 to 300 MW[45] with a capital cost of USD 1,150 to 2,300/kW_e, at 10% discount rate, 20 year plant life, and USD 3/GJ. Meta-analysis conditions	13–19[45] or US cents 4.5–6.9/ kWh	

experience and reduce technical risks. Costs are projected to be USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh) for 30 to 300 MW_e plants (see Table 2.15; Bauen et al., 2009a). Although process reliability is still an issue for some designs, niche markets have begun to develop (Kirkels and Verbong, 2011).

Even though the cost bases are not entirely comparable, the recent estimates for Fischer-Tropsch (FT) syndiesel from Bauen et al. (2009a), van Vliet et al. (2009), the National Research Council (2009a) and Larson et al. (2009) are (in USD_{2005}/GJ), respectively: 20 to 29.5, 16 to 22, 25 to 30, and 28 (coal and biomass). The breakeven point would occur around USD_{2005} 80 to 120/barrel (USD_{2005} 0.51 to 0.74/litre). High efficiency gains are expected, especially in the case of polygeneration with FT fuels (Hamelinck and Faaij, 2006; Laser et al., 2009; Williams et al., 2009).

3.5. Biomass gasification for different markets

For commercial heat production from biomass, reliable technologies (e.g. gasification, advanced stoves, etc.) are commercially available for many applications (industrial, district and domestic heating), but profitability of power generation (or CHP) seems better in most current markets. Especially, for specific industrial applications heat production from biomass seems most attractive.

Power generation from biomass by advanced combustion technology and co-firing schemes is at present the real growth market worldwide. Mature, efficient and reliable technology is available to turn biomass into power. In various markets the average scale of biomass combustion schemes rapidly increases due to improved availability of biomass resources and the economic advantages of economies of scale of conversion technology. It is also in this field that competitive performance compared to fossil fuels is possible where lower cost residues are available. This is in particular true for co-firing schemes, where investment costs can be minimal. Specific (national) policies (such as carbon taxes, renewable energy support, e.g. by direct investment subsidies or feed-in tariffs) accelerate this development. Gasification technology (integrated with gas turbines/combined cycles) offers even better perspectives for power generation from biomass on medium term and can make power generation from energy crops competitive in many areas in the world once this technology has been proven on commercial scale. Gasification (in particular larger scale CFB concepts) also offers excellent possibilities for co-firing schemes. There is clear evidence that further improvements in power generation technologies (e.g., via biomass integrated gasification/combined cycle technology), supply systems for biomass, and production of perennial cropping systems can bring the costs of power (and heat or fuels) generation from biomass down to attractive cost levels in many regions. Nevertheless, the competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems, performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion.

Integrated biomass gasification is a major avenue for the development of a variety of biofuels, with equivalent properties to gasoline, diesel and jet fuel for composition of hydrocarbon fuels. An option highlighted as promising in the literature is a fuel product ‘passing through’ the catalytic reactor only once with the remaining gas going to the power system instead of being recycled into the fuel synthesis. Other hybrid biochemical and thermochemical concepts have also been contemplated (Laser et al., 2009). Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated that upgrading of oils to blendstocks of gasoline or diesel or even jet fuel quality products is technically possible (IATA, 2009).

The benefits of biomass gasification and carbon sequestration and storage alone or with coal are significant. Similarly, capturing CO_2 from fermentation processes offers a significant option in many regions of the world, and BCCS may become an attractive medium-term mitigation option. However, such concepts are not deployed at present and cost trends are studied to a limited extent and not deployed commercially yet. Also, geologic sequestration reliability and the uncertainty of the regulatory environment pose further barriers. More detailed analysis is desired in this field.

Box 3 |

Generation and Delivery of Renewable Energy Services in CUBA, the case of Isla de la Juventud

A project executed by UNIDO (Renewable and Rural Energy Unit, Energy and Climate Change Branch)
Funded by: Global Environment Facility (GEF)
Partners: UNEP, Government of Cuba: Ministry of Energy and Mines; MINCEX, Union Eléctrica, Ministry of Agriculture and other state and non-state institution.

Background

Isla de la Juventud is the second largest island of Cuba with a great tourism potential and agricultural prospects but no grid connection to the main island. Like in most Caribbean states, high oil imports are constraining the ability of islanders to develop sustainable livelihoods. In 2011, over 90 percent of Cuba's electricity generation capacity was still fossil fuel based. Cuba produces 50 percent of oil for its domestic consumption while the rest is imported. Provision of reliable electricity at affordable prices to all households, services and industries is an integral component of the national development plan of the Government of Cuba. UNIDO, in cooperation with UNEP, has implemented a GEF funded project to promote the generation and delivery of renewable energy based modern energy services to meet the growing demand for energy on Isla de la Juventud.

Project Objective

The main objective of the project has been to reduce greenhouse gas emissions in Cuba by promoting environmentally sound renewable energy technologies for power generation and provide modern energy services. The project has addressed the key barriers that constrain the use of renewable energy technologies (biomass and wind) for power and heat generation on the Isla de la Juventud, and promoted business models for sustainable harnessing of renewable energy resources. Given the high cost of generating electricity based on fossil fuels, Isla de la Juventud presented an opportunity for an intervention to support renewable energy technologies.

The project goal has been to introduce new and innovative financial and institutional structures to encourage investments, support economically viable markets, promote environmentally sustainable forestry management and enhance local manufacturing capacity for renewable energy technologies in Cuba. Broader outcomes in Cuba should be observable in the form of project proposals and ultimately investments on a long-term basis as the business models for generation of power and process heat from renewable energy sources can be replicated in other parts of Cuba or Caribbean islands facing similar challenges.

Activities

This project has been:

- Setting up four business models on biomass production, biomass power generation, wind energy and process heat for industry;
- Building up national technical capacity in the renewable energy sector;
- Setting up a Risk and Replication Management Fund (RRMF) to promote renewable energy technologies in Cuba; and
- Strengthening policy planning mechanisms.




The project results

Biomass Gasification Power Plant Cocodrillo - 50 KW$_e$

Cocodrillo biomass gasification power plant based in the southern part of the island has been in operation since 2010 and has been generating electricity for the local community. In 2013, the electro plant has produced electricity amounting to 56 788 kWh, saving more than 18 tons of diesel fuel. This biomass gasification plant supplies electricity to 96 households (325 inhabitants), a bakery, a primary school and the water supply system.

Forest Management - 30,000 tones per year

The project has supported the development of a forest management initiative to produce 30,000 tons of biomass per year in a sustainable way to supply biomass for the power plants and industry.

Wind Farm, Los Canarreos - 1.65 MWe

Thanks to co-financing from the Government of Cuba, hurricane-proof wind turbines were erected. The wind farm Los Canarreos is fully operational. Los Canarreos has been fully funded by the Government of Cuba with an investment of around $4.5 million.

Table 6 | Electricity production in the reporting period from grid-connected renewable energy installations installed under the influence of the project (MWh / year):

	2007	2008	2009	2010	2011	2012	2013
Gross Generation (MWh)	1163.2	932.6	1030.4	1230.0	1434.7	1451.5	1075.2
Fossil fuel saved (toe)	286.86	207.35	246.2	268.43	294.3	371.8	250.5
Avoid CO2 (ton)	930.56	712.43	824.3	986.4	1073.2	1110.4	822.5

Biomass Gasification Plant, La Melvis 0.5 - 2 MWe

A large-scale biomass gasification plant has been commissioned in May 2014 in the northern part of the island. The plant is designed on a modular basis of 0.5 MW components. The technology has been provided from India as a part of a South-South Cooperation exercise.

Heat Production for Food Industry - 3.8 MWtho

A new biomass boilers are being installed in the meat processing industry to improve efficiency, financial viability and competitiveness of the company. The plant will be fully operational in the early 2015.

Risk and Replication Management Fund - USD 2.9 million

A fund has been established within Compañia Fiduciaria to finance renewable energy projects in Cuba and to set an incentive mechanism for local companies to invest into the renewable energy sector. As of September 2014, the final stage of transformation of the “Risk and Replication Management Fund” (RRMF) constituted under the project execution, into the “Cuba Renewable Energy Fund” (CREF) to support new energy projects in in Cuba is ongoing.

Part IV
Conclusions

Biomass is an essential renewable energy source to develop a low carbon future energy system on global scale. Biomass resource potentials are large enough to deliver about a quarter (i.e. 200-300 EJ) of the future worlds energy supply. Bioenergy has a significant greenhouse gas (GHG) mitigation potential, provided that the resources are developed sustainably and that efficient bioenergy systems are used. Certain current systems and key future options including perennial cropping systems, use of biomass residues and wastes and advanced conversion systems are able to deliver 80 to 90% emission reductions compared to the fossil energy baseline. However, land use conversion and forest management that lead to a loss of carbon stocks (direct) in addition to indirect land use change (d+iLUC) effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts.

Biomass is a primary source of food, fodder and fibre and as a renewable energy (RE) source provided about 10.2% (50.3 EJ) of global primary energy supply in 2008. Traditional use of wood, straws, charcoal, dung and other manures for cooking, space heating and lighting by generally poorer populations in developing countries accounts for about 30.7 EJ, and another 20 to 40% occurs in unaccounted informal sectors including charcoal production and distribution. Primary modern bioenergy for electricity, heat or transport fuels was 11.3 EJ in 2008 compared to 9.6 EJ in 2005 and the share of modern bioenergy was 22% compared to 20.6 %.

Potential deployment levels of bioenergy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential such as market and policy conditions, and strong dependence on the rate of improvement in the agricultural sector for food and feed and in wood and pulp products production.

The upper bound of the technical potential of biomass for bioenergy may be as large as 500 EJ/yr by 2050. Reaching a substantial fraction of the technical potential will require sophisticated land and water management, large worldwide plant productivity increases, land optimization and other measures. Realizing this potential will be a major challenge, but it could make a substantial contribution to the world's primary energy supply in 2050.

Bioenergy has complex societal and environmental interactions, including climate change feedback, biomass production and land use. The impact of bioenergy on social and environmental issues (e.g., health, poverty, biodiversity) may be positive or negative depending on local conditions and the design and implementation of specific projects. The policy context for bioenergy, and particularly biofuels, has changed rapidly and dramatically in recent years. The food versus fuel debate and growing concerns about other conflicts are driving a strong push for the development and implementation of sustainability criteria and frameworks. Many conflicts can be reduced if not avoided by encouraging synergisms in the management of natural resource, agricultural and livestock sectors as part of good governance of land use that increases rural development and contributes to poverty alleviation and increased energy security.

Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 - 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or combined heat and power (CHP) systems larger than about 2 MW (with feed stock costs of USD_{2005} 3/GJ_{feed} and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets) (2007-2008 data expressed in USD_{2005}, 7% discount rate, and other variables at mid-range).

Recent analyses of lignocellulosic biofuels indicate potential improvements that enable them to compete at oil prices of USD_{2005} 60 to 70/barrel (USD_{2005} 0.38 to 0.44/litre) assuming no revenue from carbon dioxide (CO_2) mitigation. Scenario analyses indicate that strong short-term research and development (R&D) and market support could allow for commercialization around 2020 depending on oil and carbon pricing. In addition to ethanol and biodiesel, a range of hydrocarbons and chemicals/materials similar to those currently derived from oil could provide biofuels for not only vehicles but also for the aviation and maritime sectors. Biomass is the only renewable resource that can currently provide high energy density liquid fuels. A wider variety of bio-based products can also be produced at biorefineries to enhance the economics of the overall conversion process. Short-term options (some of them already competitive) that can deliver long-term synergies include co-firing, CHP, heat generation and sugarcane-based ethanol and bioelectricity co-production. Development of working bioenergy markets and facilitation of international bioenergy trade can help achieve these synergies.

Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring bioenergy costs down. There is clear evidence that technological learning and related cost reductions occur in many biomass technologies with learning rates comparable to other RETs. This is true for cropping systems where improvements in agricultural management of annual crops, supply systems and logistics, conversion technologies to produce energy carriers such as heat, electricity and ethanol from sugarcane or maize, and biogas have demonstrated significant cost reductions.

Multiple drivers for bioenergy systems and their deployment in sustainable directions are emerging. Examples include rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefinery and lignocellulosic biofuel options and, in particular, development of sustainability criteria and frameworks. Sustained cost reductions of key technologies in biomass production and conversion, supply infrastructure development, and integrated systems research can lead to the implementation of strategies that facilitate sustainable land and water use and gain public and political acceptance.

Gasification technologies are one of many conversion pathways that can be deployed to convert biomass to heat, power, fuels and chemicals. Many concepts have been developed, from kW to 100's of MWth scale. When biomass co-feeding in existing coal fired gasifiers is considered, the capacity of economic conversion capacity is up to 1 GWth.

Small scale gasification technologies are technically and commercially sound for heat generation and are suited for various industries where biomass is available and process heat is required. Small scale gasification systems for power generation (or CHP operation) offer the prospect to combine rural development opportunities due to electrification, combined with use of locally available biomass fuels and fit very well in many sustainable development schemes. However, operation of such systems remains complex in many settings and the economics are not always sound.

The biomass **gasification technology is an interesting option for rural development**. It promises:

- Sustainable conversion of locally available biomass into electricity for local supplies;
- Local value chain with income generation for the suppliers of the biomass as fuel;
- Incentives for reforestation.

At the current stage, the technology may be a reasonable solution in some industrial settings where continuous qualified technical support can be guaranteed.

With biomass prices of about 2 U$/GJ state of the art combustion technology at a scale of 40 - 60 MWe can result in Costs of Electricity (COE) of around U$ct 5-6/kWh produced. Co-combustion, particularly at efficient coal fired power plants, can obtain similar or lower cost figures, largely depending on the feedstock costs.

When BIG/CC technology becomes available commercially, COE could drop further to about 3-4 U$ct/kWh, especially due to higher electrical efficiencies. For larger scales (i.e. over 100 MWe) cultivated biomass will be able to compete fully with fossil fuels in many situations. The benefits of lower specific capital costs and increased efficiency certainly outweigh the increase in costs and energy use for transport for considerable distances once a reasonably well developed infrastructure is in place [Dornburg and Faaij, 2001].

Decentralised power (and heat) production is generally more expensive, but better suited for off-grid applications. The costs that could ultimately be obtained with e.g. gasifier/diesel systems are still unclear and depend strongly on what emissions and fuel quality are considered acceptable. Combined Heat and Power generation is generally attractive when heat is required with high load factors.

Bioenergy and biomass gasification represents an important technological opportunity for industries that would like to become industrial prosumenrs for several reasons i.e.: a) energy can become an income option by using waste to generate energy , b) waste can be turned from an environmental and logistic problem to an opportunity, c) industries can be self-sufficient in terms of energy, d) electricity can be provided to the local community contributing to their development, e) industries can reduce their GHGs emissions and d) new market opportunities for green industries can be tapped.

Since an industry sector that is solely dependent on energy from fossil fuels cannot be considered sustainable, industrial prosumers of renewable energy are a central player to achieve an Inclusive and Sustainable Industrial Development.

References

Alpher H. and Stephanopoulos G. (2009), "Engineering for biofuels: exploiting innate microbial capacity or importing biosynthetic potential?," National Revue Microbiology, Oct;7(10):715-23

Arndt C., Benfica R. Tarp F. and Uaiene R. (2010): "Biofuels Poverty, and Growth: A Computable General Equilibrium Analysis of Mozambique", Environment and Development Economics, 15(1), pp. 81-105

Bauen, A., Berndes G., Junginger M., Londo M., Vuille F., Ball R., Bole T., Chudziak C., Faaij A., and Mozaffarian H. (2009a): Bioenergy; A Sustainable and Reliable Energy Source: A Review of Status and Prospects. IEA Bioenergy

Berndes G., and Hansson J. (2007): "Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels", Energy Policy, 35(12), pp. 5965-5979

Bremdal B. A., "Prosumer oriented business in the energy market", IMPROSUME Publication Series, No. 2 (2011).

Colombo E., Bologna S., and Masera D. eds. (2013), Renewable Energy for Unleashing Sustainable Development, Springer

Couture T. and Masera D., Industrial Prosumers of Renewable Energy (UNIDO, forthcoming).

Chum H., Faaij A. P.C, Moreira J. et al., Chapter 2, Bioenergy. In: Ottmar Edenhofer, Ramón Pichs Madruga, Youba Sokona et al. (eds.) The IPCC Special Report of the Intergovernmental Panel on Climate Change: Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, New York, ISBN 978-1-107-60710-12011. Pp. 209-332

Dimpl E., Small scale electricity generation from biomass: Part I: Biomass gasification. GTZ-HERA, publication, Eschborn - Germany, August 2010. Pp.14.

Dornburg Veronika, Detlef van Vuuren, Gerrie van de Ven, Hans Langeveld, Marieke Meeusen, Martin Banse, Mark van Oorschot, Jan Ros, Gert Jan van den Born, Harry Aiking, Marc Londo, Hamid Mozaffarian, Pita Verweij, Erik Lysen, André Faaij, Bioenergy Revisited: Key Factors in Global Potentials of Bioenergy, Energy & Environmental Science, February 2010, 3, Pages 258–267

FAO, 2008a: The State of Food and Agriculture 2008– Biofuels: prospects, risks,and opportunities. Food and Agriculture Organization, Rome, Italy, 138pp.

Faaij, A., R. van Ree, L. Waldheim, E. Olsson, A. Oudhuis, A. van Wijk, C. Daey Ouwens, W. Turkenburg, Gasification of biomass wastes and residues for electricity production. Biomass and Bioenergy, Vol. 12 No. 6, 1997.

Faaij A., B. Meuleman, R. Van Ree, Long term perspectives of BIG/CC technology, performance and costs, Department of Science, Technology and Society, Utrecht University and the Netherlands Energy Research Foundation (ECN), report prepared for NOVEM (EWAB 9840) December 1998.

Faaij A., Modern biomass conversion technologies. Mitigation and Adaptation Strategies for Global Change, Volume 11, No. 2, March 2006, Pages 335-367.

Hellwinckel, C. M., T. O. West, D. G. De La Torre Ugarte, and Perlack, R. 2010. Evaluating possible cap and trade legislation on cellulosic feedstock availability. Global Change Biology Bioenergy 2:278-287.

Hunt S., Easterly J. et al."Biofuels for Transport: Global Potential and Implications for Energy and Agriculture" prepared by Worldwatch Institute, for the German Ministry of Food, Agriculture and Consumer Protection (BMELV) in coordination with the German Agency for Technical Cooperation (GTZ) and the German Agency of Renewable Resources (FNR), ISBN: 1844074226 , published by EarthScan/James & James, April 2007 Pp. 336

IEA-RETD, "Residential Prosumers: Drivers And Policy Options (Re-Prosumers)", 2014. Available at: http://iea-retd.org/archives/publications/re-prosumers

IPCC-SRREN, 2011; H. Chum, A. Faaij, J. Moreira, (CLA's), Berndes, Göran; Dhamija, Parveen; Dong, Hongmin; Gabrielle, Benoît, X; Goss Eng, Alison M; Lucht, Wolfgang; Mapako, Maxwell; Masera Cerutti, Omar; McIntyre, Terry Charles; Minowa, Tomoaki; Pingoud, Kim, Bain, Richard; Chiang, Ranyee; Dawe, David; Heath, Garvin; Junginger, Martin; Patel, Martin;Yang, Joyce C.; Warner, Ethan, Chapter 2, Bioenergy. In: Ottmar Edenhofer, Ramón Pichs Madruga, Youba Sokona et al. (eds.) The IPCC Special Report of the Intergovernmental Panel on Climate Change: Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, New York, ISBN 978-1-107-60710-12011, pp. 209-332

IRENA, "REMAP Project". Available from: http://irena.org/remap/

IRENA, "Renewable Power Generation Costs in 2012: An Overview", 2013. Available from: http://costing.irena.org/media/2769/Overview_Renewable-Power-Generation-Costs-in-2012.pdf

Kukoyi D., "The Concept of Embedded Generation – Prospects and Challenges." Presented at the Workshop On The Embedded Generation Framework In The Nigerian Electricity Supply Industry, (Nov 15). Available from: http://www.detailsolicitors.com/media/archive3/seminars/workshop_on_embedded_power/presentations/Embedded%20Generation%20-%20Prospects%20and%20Challenges.pdf

Laufer D. (2009): Holzvergaseranlage für die Dorfgemeinschaft Batgugammana Extract of PHD thesis. Unpublished. Describes management and economics of one 12 kW gasifier plant in a village in southern Sri Lanka.

Oseni M. O., "Power Outages and the Costs of Unsupplied Electricity : Evidence from Backup Generation among Firms in Africa". Available from: http://www.usaee.org/usaee2012/submissions/OnlineProceedings/IEE%20PAPER%20FRST%20YEAR%20EDITED%20LAST%201%20LATEST.pdf

Oyedepo S.O., "Energy and sustainable development in Nigeria: the way forward", Energy, Sustainability and Society, vol. 2 No. 15 (July 2012).

Petersson A. and Wellinger A., Biogas upgrading technologies – developments and innovations, IEA Bioenergy, http://www.bpex.org.uk/downloads/300700/297762/Biogas%20Upgrading%20Technologies%20-%20Development%20and%20Innovations.pdf

Rickerson W. et al., "Residential Prosumers: Drivers and Policy Options (Re-Prosumers) "

Shandurkova I., Bremdal B.A, Bacher R., Ottesen S., and Nilsen A., "A Prosumer Oriented Energy Market: Developments and future outlooks for Smart Grid oriented energy markets", IMPROSUME Publication Series, No. 3 (2012).

Smeets E. M.W., Faaij A. P.C., Lewandowski I.M., Turkenburg W.C., A quickscan of global bio-energy potentials to 2050. Progress in Energy and Combustion Science, Volume 33, Issue 1, February 2007, Pages 56-106

UNIDO, "Inclusive and Sustainable Industrial Development", 2014. Available from: http://www.unido.org/fileadmin/user_media_upgrade/Who_we_are/Mission/ISID-Brochure-LowRes1_EN.pdf

Van Dam J., Junginger M., Faaij A.P.C., From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning, Renewable and Sustainable Energy Reviews, Volume 14, Issue 9, December 2010, Pages 2445-2472.

Van Vuure, D. P., Isaac M., and Kundzewicz Z. W. (2009a). Scenarios as the Basis for Assessment of Mitigation and Adaptation. In Hulme, M., and Neufeld, H., eds., Making climate change work for us, Cambridge University Press

World Bank, "Enterprise Surveys: Infrastructure", 2014. Available at http://www.enterprisesurveys.org/.


SCREW CONVEYOR
12A

ENERGY AND CLIMATE CHANGE BRANCH

UNIDO RENEWABLE ENERGY UNIT

renewables@unido.org

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna International Centre · P.O. Box 300 · 1400 Vienna · Austria
Tel.: (+43-1) 26026-0 · E-mail: info@unido.org
www.unido.org